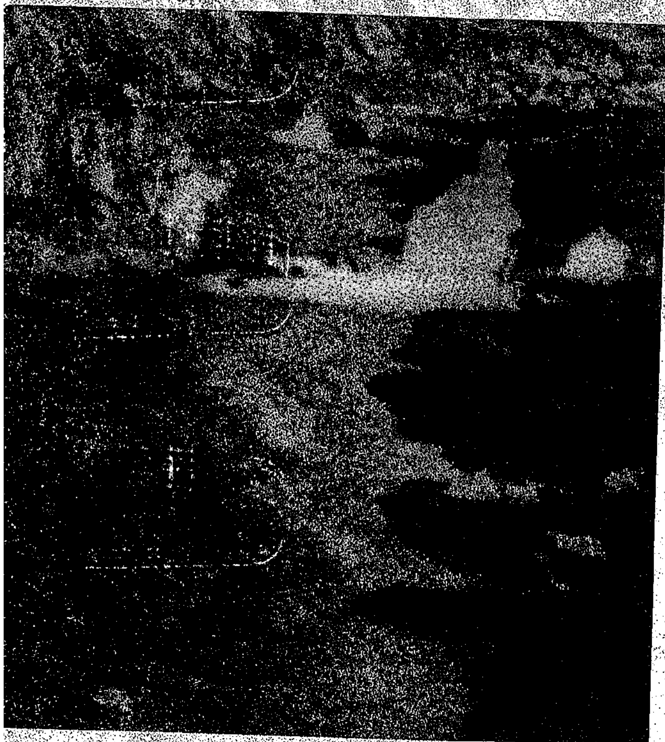


COASTAL NATURAL HAZARDS

Science, Engineering, and Public Policy

Edited by James W. Good and Sandra S. Ridlington

Oregon Sea Grant
ORESU-B-92-001

COASTAL NATURAL HAZARDS

Science, Engineering, and Public Policy

Edited by James W. Good

and Sandra S. Ridlington

Oregon Sea Grant
ORESU-B-92-001

Oregon Sea Grant, Oregon State University, Administrative
Services A402, Corvallis, Oregon 97331-2134

ISBN 1-881826-00-7

Contents

PUBLIC POLICY

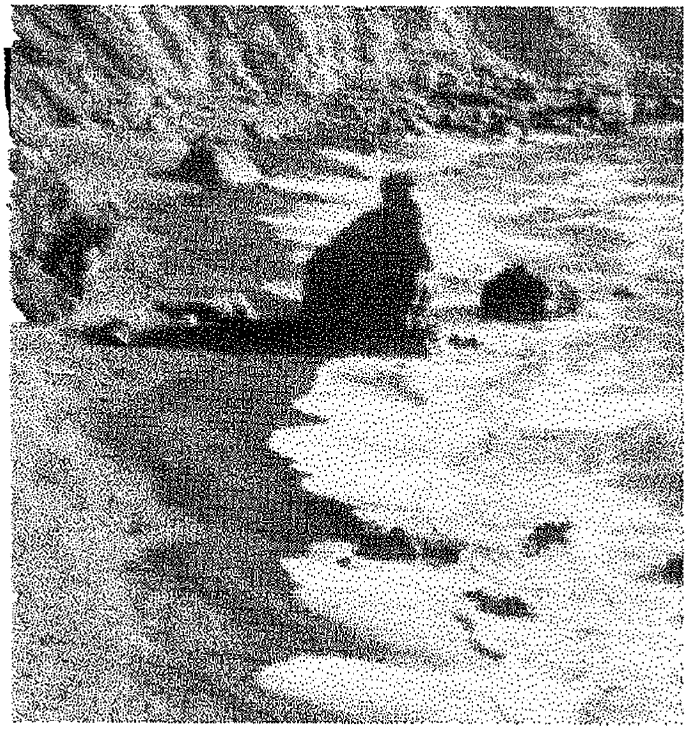
SUPPORT

This book is funded by the National Oceanic and Atmospheric Administration, through Oregon Sea Grant (grant number NA89AA-D-SG108). The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

PREFACE

In early October 1991, more than 160 coastal geologists, oceanographers, engineers, planners, resource managers, and citizens gathered in Newport, Oregon, to learn about recent research on coastal natural hazards and discuss the implications for coastal development and management. At that conference, "Coastal Natural Hazards: Science, Engineering, and Public Policy," distinguished scientists, engineers, and policy analysts reviewed the state of knowledge in their specialties. We learned about the effects of periodic El Niños on beach and shore erosion and about recent research on factors that control sea cliff erosion. Scientists presented evidence for periodic great subduction zone earthquakes that have occurred along the Pacific Northwest coast and speculated on when the next quake might strike. We were introduced to planning and engineering approaches to hazard mitigation on the West Coast and learned about the successes and shortcomings of public policies designed to deal with development in hazardous areas.

This book is a collection of the principal papers delivered at that conference, along with critiques and supplementary remarks of panelists. For the most part, the papers are written in nontechnical language, with ample illustrations. As such, they serve as useful primers for the newcomer to the subject, whether a local official, property owner, realtor, or coastal visitor. Together, the papers should also be a useful reference for the policymaker, emergency manager, professional planner, beach and coastal manager, academic, and student. And for long-time observers of the coastal scene, the papers will confirm many of their hunches about the workings of our dynamic Pacific Northwest coastline.



SCIENCE

SEISMIC HAZARDS ON THE OREGON COAST

SCIENCE

PACIFIC NORTHWEST COASTAL EARTHQUAKE, TSUNAMI, AND LANDSLIDE HAZARDS

Ian Madin
Oregon Department of Geology and Mineral Industries

Seismic hazards have been considered a relatively minor threat in Oregon for most of our recorded history. Recent advances in the geological and seismological understanding of earthquakes in Oregon changed this perception during the 1980s, and there is now fairly widespread acceptance among the scientific community that Oregon, particularly coastal Oregon, faces significant seismic hazards. In this paper I explain the changes in scientific understanding that led to this conclusion and describe the many types of hazards associated with earthquakes. In addition, I illustrate examples of the evaluation of hazard-prone areas, using the coastal geologic hazard maps published by the Oregon Department of Geology and Mineral Industries (DOGAMI).

This paper is intended for a lay audience. Thus, in the interest of clarity, I have omitted many arguments and details of the scientific data. Although I cite many sources, the paper is not a complete review of the existing literature.

Plate Tectonics: The Driving Force

The theory of plate tectonics explains the large-scale structure of the surface of the earth and major earth movements. The theory is based on the assumption that the rigid outer rock shell of the earth, called the crust, is essentially floating on a plastic or semiliquid layer 100-150 kilometers deep in the earth's mantle (figure 1). Over hundreds of millions of years, circulation in the body of the earth has broken the crust into fragments the size of continents. These fragments are called plates, and as they move slowly across the face of the earth, they interact with each other along their edges, producing earthquake and volcanic activity. The boundaries between plates take one of three forms: divergent boundaries, where plates pull apart; convergent boundaries, where plates come together; and transform boundaries, where plates slide horizontally past one another.

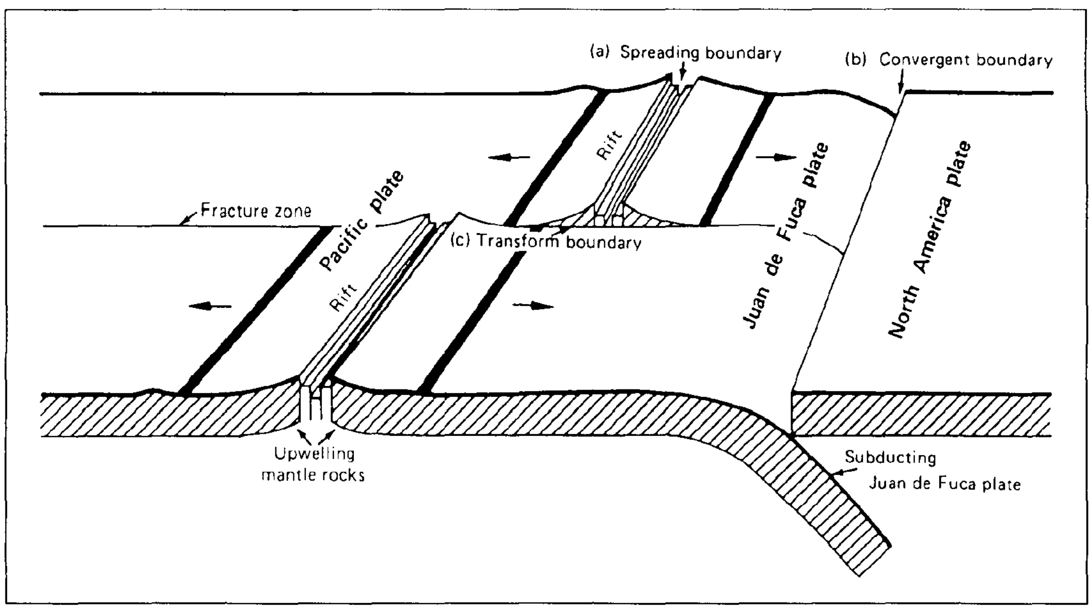


Figure 1. Three types of plate boundaries. A spreading boundary (a) marks the divergence of two plates. A convergent boundary (b) occurs where one plate moves toward another. A transform boundary (c) occurs where relative plate motion is parallel to the plate edges. After Noson and others, 1988.

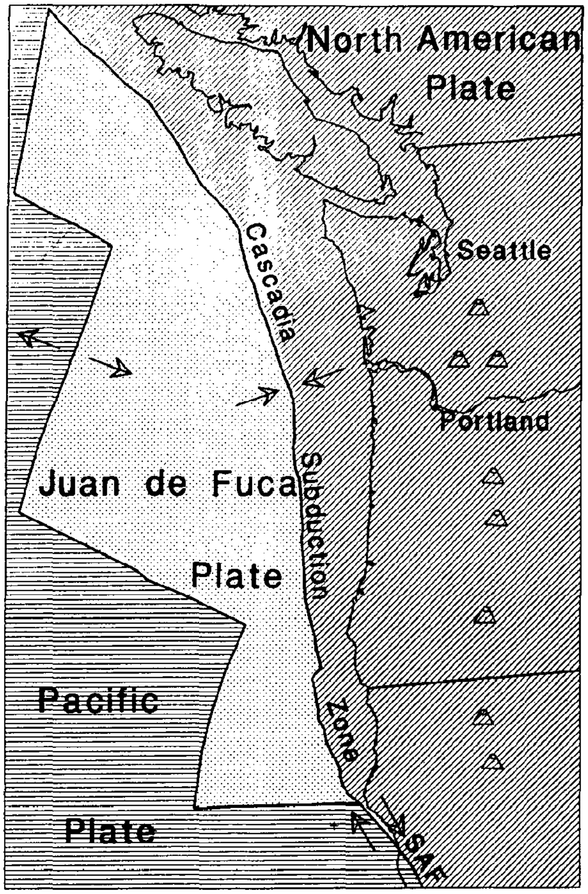


Figure 2. Plate tectonic setting of the Pacific Northwest.

At divergent boundaries, spreading centers form where lava erupts along the length of the boundary, congealing to form new crust. As the plates continue to pull apart, the newly formed crust splits, half with each plate, and this process creates tens to hundreds of kilometers of new crust over millions of years. The crust formed by this process is composed of dense basalt rock, which floats low in the mantle and therefore makes up the floors of the earth's oceans.

Where two plates collide in a convergent boundary, one will typically duck beneath the edge of the other and be pushed or pulled several hundred kilometers into the depths of the earth. This process is called subduction. When the subducted plate is sufficiently deep, it melts; the resultant magma rises to feed a chain of volcanoes parallel to the convergent boundary. This kind of plate boundary, called a subduction zone, consumes the crust produced at spreading centers.

At a transform boundary, two plates simply slide past each other horizontally, and crust is neither produced nor consumed.

Around the world, the majority of earthquake and volcanic activity is concentrated along the plate boundaries. Spreading centers produce huge, but relatively quiet, eruptions of basalt. Subduction zone volcanic chains create smaller, but often explosive, eruptions of lava and ash. Spreading centers produce normal fault earthquakes, caused by the pulling apart of the crust, which are typically no larger than magnitude 6 or 7. Transform boundaries create earthquakes up to magnitude 8 along horizontal slip faults, where the opposite sides of the fault move horizontally past each other. Subduction zones produce thrust earthquakes, where one side of the fault is shoved beneath the other. These subduction earthquakes are the largest recorded, with magnitudes commonly greater than 8. Subduction zones also produce intraplate earthquakes up to magnitude 7 or 8 in the subducting plate, as it buckles on its way down into the body of the earth.

Cascadia: The Faults under Our Feet

The Pacific Northwest is endowed with examples of all three types of plate boundaries, as three plates interact in the region. Oregon is situated on the North American Plate (figure 2), which stretches from the Pacific coast of the U.S. to the middle of the Atlantic Ocean. To the west of the North American Plate is the Pacific Plate, the largest on the planet, which extends to Alaska, Japan, and Antarctica. Last and least, sandwiched between these two giant plates is the Juan de Fuca Plate, which forms the deep ocean floor just off the coast of Oregon and Washington. The Pacific and North American plates share a transform boundary in California (San Andreas Fault) and northern British Columbia (Queen Charlotte Fault), and the Pacific Plate moves inexorably north past North America along these two great horizontal slip faults. Dozens of major historical earthquakes on these transform faults clearly indicate that these are active plate boundaries. The Juan de Fuca and Pacific plates are separated by a spreading center, which is very seismically active and which has experienced undersea volcanic eruptions in the last few years. Finally, there is a subduction zone plate boundary between the Juan de Fuca and North American Plates. The Juan de Fuca Plate slides beneath the North American Plate along a great fault that extends from Cape Mendocino in California to Vancouver Island in British Columbia. This great fault is called the Cascadia subduction zone (CSZ). The CSZ originates (figure 3) at the base of the continental slope off Oregon and Washington, and angles gently beneath the North American Plate. It reaches a depth of 100 to 150 kilometers beneath the high Cascades, where the Juan de Fuca Plate melts to feed the Cascade volcanoes. As such, this great fault underlies virtually all of Oregon, and along the coast it may be as little as 30 or 40 kilometers down. Because all of the other plate boundaries in the area and the Cascade volcanoes are active, we conclude that the CSZ is also active. The Juan de Fuca Plate is probably subducting along the CSZ at 3.8 to 4.8 centimeters per year (Riddihough 1984), a rate quite similar to the 3.3 to 4.8 centimeters per year measured and estimated on the San Andreas Fault (Harbert 1991). The clear conclusion is that Oregon sits on top of the CSZ, a major active plate boundary fault.

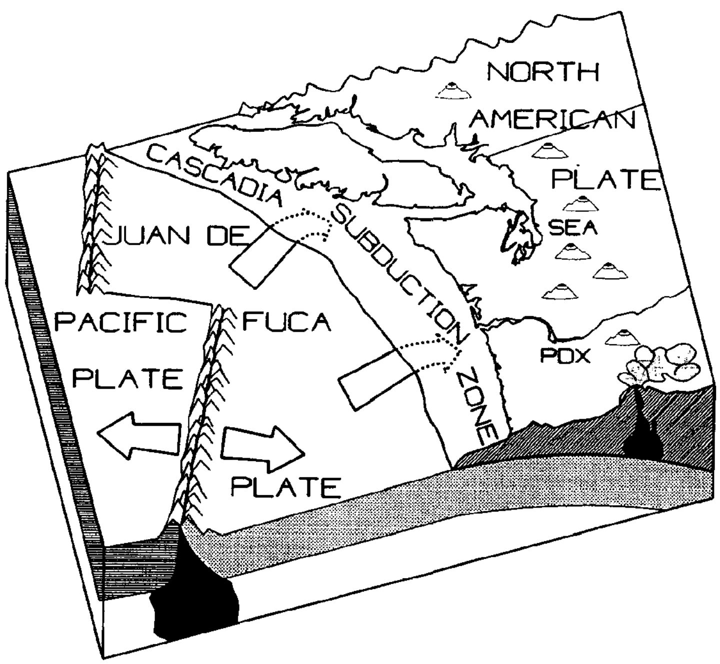


Figure 3. Schematic cross section of the Cascadia subduction zone (CSZ).

Earthquake Sources: The Triple Threat

From our understanding of the plate tectonic setting of the Pacific Northwest, we can identify three possible earthquake types (figure 4): crustal, intraplate, and subduction. Each of the three types occurs in geographically discrete source zones. Although the three types have distinct characteristics, they are all driven by the convergence of the North American and Juan de Fuca plates across the CSZ. Crustal earthquakes occur within the North American Plate at depths of 10 to 20 kilometers. Intraplate earthquakes occur within the descending Juan de Fuca Plate at depths of 40 to 60 kilometers. Subduction earthquakes are hypothetical, as none have been observed, but they are believed to occur in the upper portion of the CSZ, along the great fault which separates the two plates.

Crustal Earthquakes: Close to Home

In Oregon, the majority of historical earthquakes have probably been crustal events. Most of these earthquakes have occurred in the Portland area, the Willamette Valley, the northern Oregon Cascades, and eastern Oregon. Coastal Oregon has been almost completely devoid of earthquakes, with the exception of a cluster of small events near Newport, and the 1863 Port Orford earthquake (Jacobson 1986; Johnson and Scofield 1991), both of which occurred before the establishment in 1970 of modern seismic networks in the Pacific Northwest. As a result, it is not known whether these earthquakes are crustal or intraplate. The history of seismicity along the

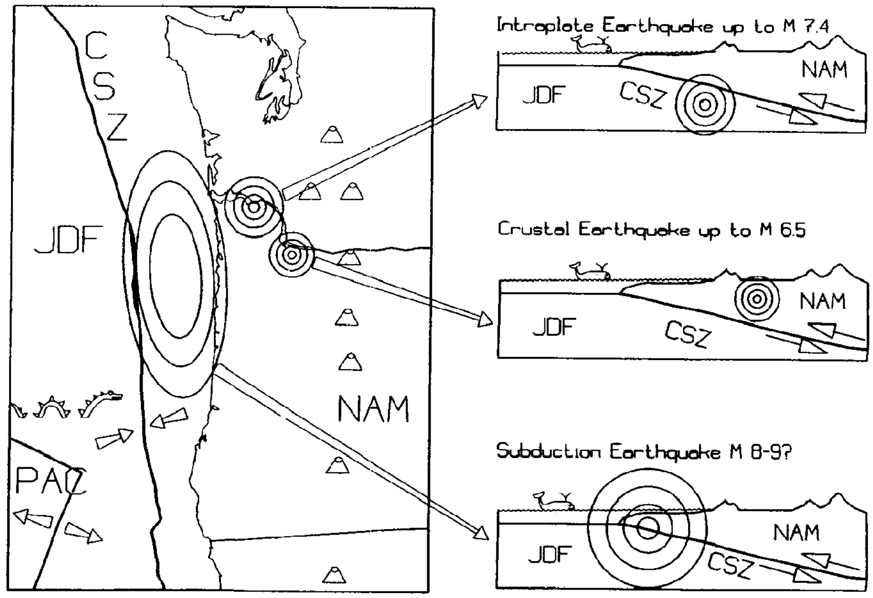


Figure 4. Earthquake source zones in the Pacific Northwest. CSZ = Cascadia subduction zone; JDF = Juan de Fuca Plate; NAM = North American Plate; PAC = Pacific Plate.

Oregon coast may suggest that there is little threat from crustal earthquakes. However, the record of historical seismicity extends only to 1841, and instrumental measurement of earthquakes in Oregon began only in the late 1950s.

The geologic record suggests that crustal earthquakes may pose some hazard at a few sites along the coast. McInelly and Kelsey (1990) reported numerous faults in the South Slough-Charleston region of Coos Bay that may represent a seismic hazard (figure 5). The various faults have broken and offset marine terrace deposits that are probably only 80,000 to 120,000 years old and hence may have some potential for future movement. The mapped extent of these faults is short, which may suggest that they are not capable of generating earthquakes greater than magnitude 5 to 6. Work in progress (Harvey Kelsey, personal communication, 1991) suggests faults near Alsea Bay which offset marine terrace deposits, also a few hundred thousand years old. Finally, detailed offshore geologic mapping (Goldfinger and others 1990) has identified dozens of major offshore crustal faults that appear to have moved in at least the last 1.6 million years (Pleistocene time), possibly as recently as the last 10,000 years (Holocene time). These faults pose a potential threat, particularly if they extend onshore. Similar offshore crustal faults have been responsible for significant historical earthquakes, including the magnitude 6.6 earthquake of July 12, 1991, which occurred 110 kilometers west of Brookings. If that earthquake had been 50 kilometers closer, damage could have been widespread. Where potentially active crustal faults occur beneath urban areas, the possibility exists for damaging earthquakes.

From what is now known, most of the Oregon coast is probably not greatly at risk from crustal earthquakes. Detailed fault mapping of the coast has been in progress for only a few years, and seismic monitoring capabilities on the coast have

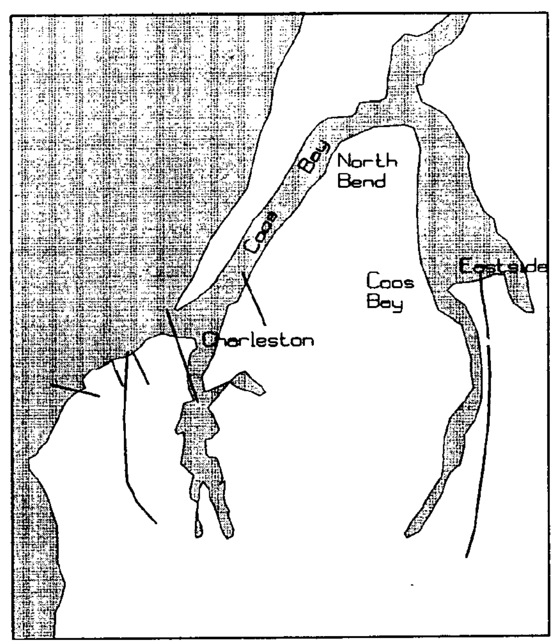


Figure 5. Schematic map of known Quaternary faults in the Coos Bay area. After McInelly and Kelsey, 1990.

always lagged behind the rest of the state. Improved seismic monitoring by the University of Oregon and University of Washington should help to define potential crustal faults along the coast. Ongoing coastal fault studies by Western Washington State University (Harvey Kelsey), University of Oregon (Ray Weldon), the U.S. Geological Survey (Ray Wells, Parke Snavely) Oregon State University (Vern Kulm, Chris Goldfinger, John Dilles), and DOGAMI (Ian Madin) should also provide a more reliable estimate of crustal earthquake hazards.

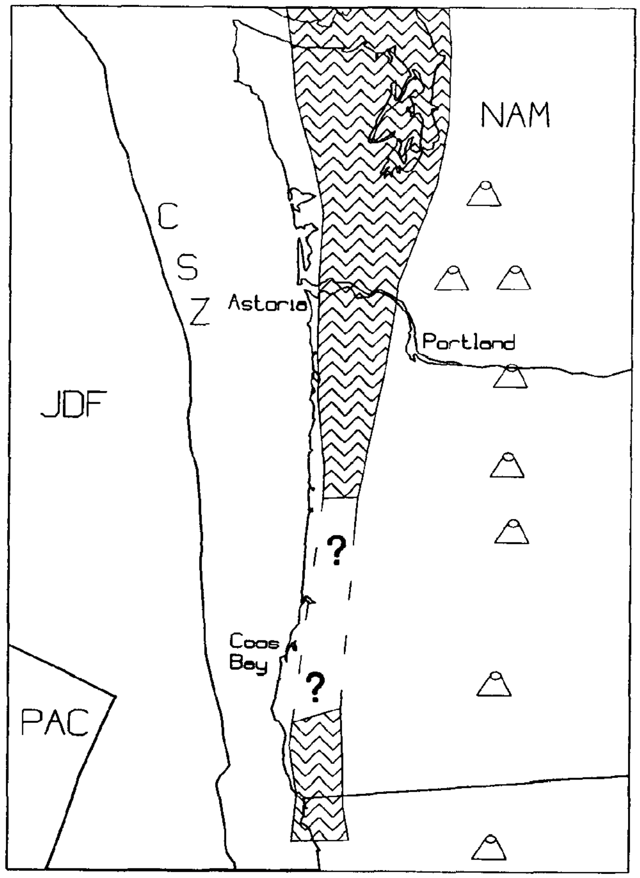


Figure 6. Potential source zone for magnitude 7+ intraplate earthquakes. From Weaver and Shedlock, 1989.

Intraplate Earthquakes: Danger in the Depths

In western Washington, the majority of damaging historical earthquakes have been intraplate earthquakes, which occur in the descending Juan de Fuca Plate (figure 4). The largest of these earthquakes was the magnitude 7.1 Olympia earthquake of 1949. Along the Oregon coast, a small number of earthquakes have been positively identified as intraplate events. The largest of them was a magnitude 2.8 event that occurred at a depth of 41 kilometers near Newport in June 1981 (Weaver and Baker 1988). This suggests that many of the other earthquakes located in the Newport area before 1970 may have been intraplate events. The largest intraplate event in Oregon may have been the 1873 magnitude 6.7 Port Orford earthquake. This event was felt along the southern Oregon and northern California coasts and had no aftershocks. The absence of aftershocks has led to speculation that it was an intraplate earthquake: intraplate earthquakes typically do not have aftershocks (Ludwin and others 1989). Weaver and Shedlock (1989) have proposed that much of the Oregon Coast from Astoria to Waldport and from Cape Blanco to the California border is susceptible to intraplate earthquakes as large as magnitude 7 (figure 6).

No amount of surface geological investigation will improve our understanding of intraplate earthquakes, which occur 45 to 60 kilometers beneath the surface. Improved seismic monitoring capabilities being installed by the Universities of Washington and Oregon will provide a more reliable estimate of the hazard of intraplate earthquakes. It is clear that a major source of potential earthquakes as large as magnitude 7 underlies the entire Oregon coast, but it is not clear whether these earthquakes will happen sufficiently often to present a significant hazard.

Subduction Earthquakes: The Big One

No large earthquakes have been reported from the CSZ during the 150 years of recorded history in the Pacific Northwest, and modern seismic networks detect essentially no earthquakes in the zone. This has led seismologists to speculate that subduction on the CSZ, although almost certainly active, is aseismic and never produces large earthquakes (Ando and Balazs 1979). However, Heaton and Kanamori (1984) discussed the seismic potential of the CSZ and noted that it shared many characteristics with other subduction zones which had great earthquakes. They concluded that the Juan de Fuca Plate was similar to other subduction zones in which active subduction was accompanied by a great earthquake of magnitude

8 or larger. Adams (1984) studied modern deformation of the CSZ using leveling, tide gauge, and geomorphic data and concluded that it was possible that subduction was accomplished during great subduction earthquakes every 200 to 500 years. Adams also noted that it might be possible to search for evidence of prehistoric great earthquakes by looking for disturbed layers in lake sediments, landslides triggered by earthquakes, periodic submarine landslide deposits, and uplifted or subsided coastal features. Other researchers (Byrne and others 1988) contended that the rocks in the CSZ are sufficiently weak and hot that they act in effect as a lubricant, allowing subduction to proceed without any great earthquakes. The picture is further complicated by the example of the San Andreas fault, which has "aseismically" creeping segments, which produce constant microearthquakes, and an almost completely aseismic segment, which moved in 1906 to produce the great San Francisco earthquake. Without direct evidence, the earlier debate was largely academic, as there was no way to prove or disprove the hypothesis of great earthquakes on the CSZ.

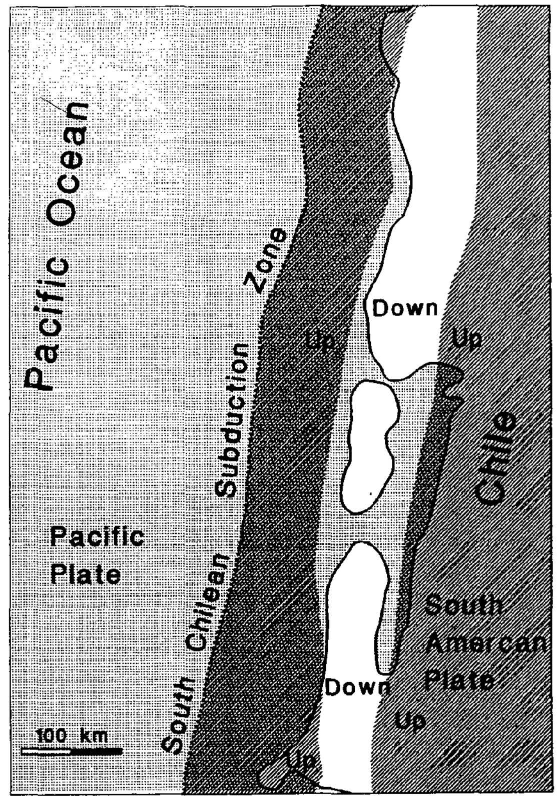


Figure 7. Schematic diagram of land level changes that occurred during the 1960 Chilean earthquake (Mw 9.5). After Plafker, 1972.

Buried Marshes: The Smoking Gun

The theoretical arguments about whether or not the CSZ moved in periodic great earthquakes were overshadowed by Brian Atwater's (1987) discovery of direct geologic evidence for prehistoric great earthquakes. Atwater's study was the first to find direct evidence of great CSZ earthquakes and was based on looking for the geologic footprint of a great earthquake. Other great subduction earthquakes around the world—Alaska, 1964, and Southern Chile, 1960 (Plafker 1972)—produced distinct and gigantic footprints on the land. Typically, the upper plate in the subduction zone undergoes immediate and permanent land level changes during a great subduction earthquake with a pattern as shown in figure 7. The leading edge of the upper plate is uplifted, with subsidence farther inland and less pronounced uplift farther inland yet. The simple mechanical explanation for this pattern is that during the hundreds of years between earthquakes, the two plates are locked together but still converging. This steady convergence causes the upper plate to flex slowly, as shown in figure 8. When the earthquake occurs, the flex is released and the land rises or subsides accordingly. The earthquake cycle produces a distinctive pattern of land level changes, with slow steady uplift or subsidence between earthquakes that instantaneously reverses during the earthquake. This phenomenon can be used in effect as a natural seismograph to record prehistoric earthquakes, because the sea leaves a "ring around the bathtub" on the land. As the land moves up and down with respect to sea level, coastal processes leave geologic features and deposits that form at very specific elevations. Where the land is uplifted, wave-cut platforms or beach ridges formed at or below mean tide level are often stranded high above the highest tides. Where the land subsides, freshwater marshes or lowland forest lands may sink below the level of the tides and be converted to intertidal mudflats.

Atwater (1987) studied Willapa Bay in southwestern Washington, where he noted a distinctive pattern of sediment in the banks of tidal channels in modern marshes. Typically, the modern vegetation would be found growing on a modern

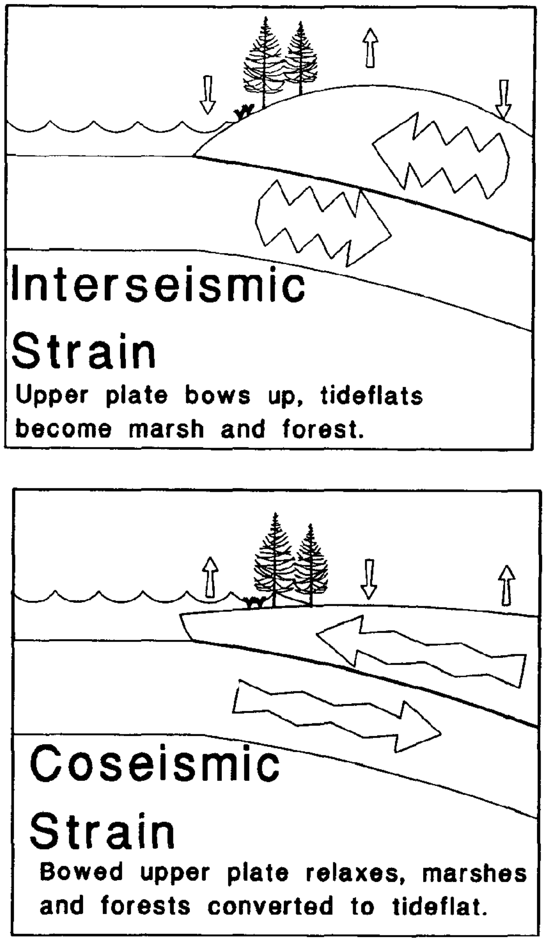


Figure 8.

peat, which would grade down into deposits of intertidal mud. This sequence suggests that the land slowly rose with respect to sea level, exposing tide flats above the range of tides and allowing freshwater plants to colonize the surface. However, beneath this sequence, Atwater found a buried, fossilized peat layer (figure 9) separated from the overlying intertidal mud by an abrupt boundary. The fossilized peat in turn graded downwards into intertidal mud, underlain by yet another layer of buried peat. This sequence of alternating buried peat and intertidal mud strongly suggests that the land has undergone cycles of slow uplift that allow marshes to colonize mudflats, followed by abrupt subsidence that buries the marsh in intertidal mud. This is exactly the sequence of deposits expected to form during cycles of great earthquakes and is in fact quite similar to buried marsh and forest deposits formed during the 1964 Alaskan and 1960 Chilean (Atwater 1989) earthquakes. Atwater also observed sand layers directly above several of the buried marsh peats, which he speculated might have been deposited by tsunamis (popularly known as tidal waves) generated by the same earthquake that caused the subsidence.

Atwater's discovery provided the first geologic evidence that great megathrust earthquakes might have occurred before the arrival of Europeans in the Pacific Northwest, but there were still many skeptics, many unanswered questions. Perhaps the burial of the marshes was due to floods, storm surges, breaches of spits, distantly generated tsunamis, or periodic great forest fires that choked streams with silt and filled in bays. Alternatively, it might be possible that the land had indeed subsided in an earthquake, but in a minor earthquake on a local fault instead of a great earthquake stretching from Vancouver Island to California.

Subsequent to Atwater's original research in Willapa Bay, other researchers began to explore Oregon estuaries for similar evidence. They found it in almost every significant estuary along the northern and central coast (figure 10). Grant and McLaren (1987) found evidence for several episodes of abrupt marsh subsidence and burial at the Salmon and Nehalem River estuaries. Peterson and Darienzo (in press) and Darienzo and Peterson (1988, 1990) discovered multiple abruptly buried marshes in the estuaries of the Necanicum, Nestucca, Little Nestucca, Siletz, Alsea, and Yaquina rivers, and at Netarts Bay. Nelson and Personius (in press) have found buried marshes in South Slough, and Peterson and Darienzo (personal communication, 1991) have detected preliminary evidence of buried marshes in the estuaries of the Siuslaw, Coquille, and Umpqua rivers, and in Catching Slough, although Nelson and Personius (in press) found conflicting evidence in these estuaries. In northern California, Carver (1991) discovered buried marsh layers in Humboldt Bay.

Clearly, the phenomenon of abruptly buried marshes is not due solely to local faults in Washington. All along the Cascadia subduction zone, repeated cycles of slow uplift followed by rapid submergence of the land have occurred, with many submergence events accompanied by tsunamis. The simplest explanation for these deposits is the periodic occurrence of great subduction earthquakes that involve hundreds of

Figure 9. Buried marsh exposed in tidal channel, Willapa Bay, Washington. Modern marsh grades down into intertidal mud, which abruptly overlies buried marsh (dark band at bottom). Thin grey layers labelled "s" are tsunami sand deposits. From Atwater and Yamaguchi, 1991.

kilometers of the coast all at once. If true, the implications for Oregon coastal communities are awesome, because such an earthquake would cause simultaneous strong shaking and coastal subsidence, which would be followed quickly by a local tsunami.

Corroborating Evidence: More Pieces of the Puzzle

Although the evidence from buried marshes is fairly persuasive, it is vital to look for other evidence to prove the great earthquake hypothesis.

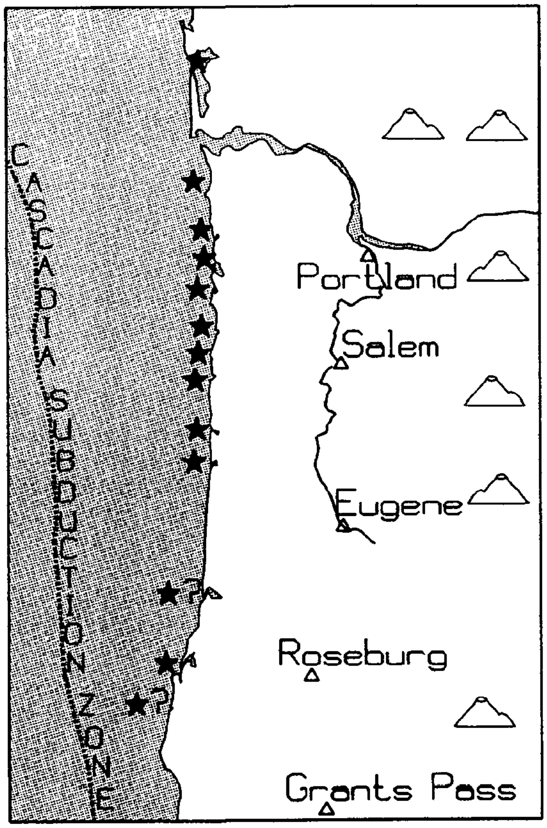


Figure 10. Sites with multiple buried marshes on the Oregon coast.

The adverse consequences of spending money and restricting coastal development unnecessarily in response to a false subduction earthquake threat are probably outweighed only by the consequences of preparing inadequately for a true threat. Although earthquake-related subsidence remains the only satisfactory explanation for the buried marshes, it is important to look for other types of evidence. To date this has come from undersea landslides, modem geodetic measurements, Indian legends, and archaeological sites.

Adams (1990) has proposed a completely independent line of evidence for great subduction earthquakes based on submarine landslide deposits. Sand, silt, and clay flushed into the coastal waters of Oregon and Washington by rivers accumulate in thick deposits offshore on the continental shelf and slope. Periodically these piles become unstable and slump in a submarine landslide, causing a slurry of sediments and water (called a turbidity current) to flow down submarine channels onto the deep abyssal plain. Each turbidity current leaves a distinctive layer of sediment, called a turbidite, and it is possible to count the number of turbidity currents that have passed any given site by counting the turbidite layers. Griggs and Kulm (1970) first noted that sediment cores from a number of submarine channels off the coast of Oregon and Washington could be used to count the number of turbidity currents that had occurred since the eruption of Mt. Mazama (now Crater Lake) about 7,000 years ago. They determined this by counting the number of turbidites above the first layer which contained the distinctive ash from Mt. Mazama. In his analysis, Adams (1990) noted that there were similar numbers of post-Mazama turbidites in the upper reaches of many channels along the coast. Most important, he noted that even where two channels came together, there were the same number of turbidites below the confluence as above. This requires the turbidity currents in each channel to have been triggered simultaneously. Adams (1990) argues that the only plausible explanation for simultaneous triggering of turbidity currents at sites tens to thousands of kilometers apart is a great subduction earthquake.

Geodetic techniques compare very precise measurements of the position and elevation of a network of stations over time to determine how the land is currently expanding or contracting, rising or falling. The first attempt to use geodetic data to constrain the behavior of the CSZ was by Ando and Balazs (1979), who used historical leveling data to show that the Oregon Coast Ranges were tilting to the east. They concluded that the Juan de Fuca Plate was subducting ascismically and would not have great earthquakes. Adams (1984) looked at historical data as well as geologic data to determine long-term deformation rates all along the CSZ. He concluded that the modem deformation did not require aseismic subduction and suggested that great earthquakes might occur. Vincent (1989), and later Weldon (1991), used historic leveling data and tidal records along the Oregon coast and across the Coast Ranges to show that parts of the coast are clearly rising at a significant rate. This result is very important because it shows clearly that the Juan de Fuca and North American plates are in fact locked together, and not slipping aseismically past one another on some layer of sedimentary "grease." Both studies note that the amount of geodetically measured uplift is dramatically less along the north-central Oregon coast than areas farther north or south (figure 11), which suggests that the subduction zone is broken into small independent segments.

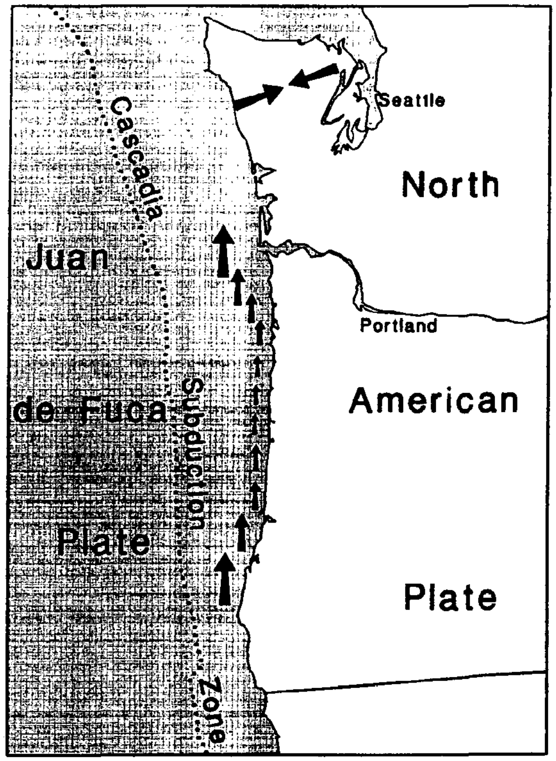


Figure 11. Schematic representation of geodetically measured deformation in the Pacific Northwest. Vertical data in Oregon from Weldon, 1991. Horizontal data in Washington from Savage and Lisowski, 1991.

In Washington, Savage and Lisowski (1991) measured the ongoing deformation of the Olympic Range with precision laser instruments. They concluded that the Olympics are currently being shortened horizontally in a direction essentially parallel to the direction of subduction of the Juan de Fuca plate (figure 11), and this shortening is consistent with the accumulation of strain energy on a locked subduction zone.

These preliminary results from geodetic studies still leave questions about the shape of the locked portion of the subduction zone and about our current position in the strain cycle, but they are inconsistent with the notion of subduction without great earthquakes.

Indian legends of great earthquakes and tsunamis are known from the Pacific Northwest. Heaton and Snavely (1985) report several legends from the region. One legend of the Makah Indians at Neah Bay recorded by James Swan states that the waters of the bay receded dramatically for four days, then returned to flood the land for another four days before receding. The same legend described a permanent land level change at the same time, with an island being converted to a peninsula, although it also noted that the water that flooded the community was hot. Woodward (1990) reports a similar tsunami legend from the Tillamook area. Unfortunately, Indian legends are somewhat ambiguous about the timing of events, and contain enough references to clearly supernatural occurrences that they provide only weak corroborating evidence to the great earthquake hypothesis.

More concretely, Woodward (1990) noted archaeological evidence for significant changes in the lifestyles of Indians along the coast of Oregon which have occurred at times coincident (see discussion below) with hypothetical prehistoric subduction earthquakes. At Nehalem Bay, Woodward reports an Indian campsite dated to 380 years before the present (BP) that is now permanently below tidal levels. In Tillamook Bay, changes in species of shellfish deposited in middens suggest a change from a bay environment to open shore at 1070 years BP. At Netarts Bay, shell middens at an Indian campsite formed 1,400 years ago have now subsided below the level of high tides. The results from these sites and others are intriguing, but they provide only circumstantial evidence of major, perhaps catastrophic changes in coastal Indian settlements that may have accompanied great earthquakes.

The evidence listed above is consistent with a history of great megathrust earthquakes in the Pacific Northwest, and a majority of geoscientists working in the region now accept that these events have occurred. There are, however, problems with the theory of great subduction events, which are reviewed in the following section.

Conflicting Evidence: It's Not a Done Deal

One of the most fundamental problems with the great earthquake story is the assumption that the buried marsh layers are in fact due exclusively to abrupt land subsidence during earthquakes. Alternating layers of peat and intertidal mud are known from coastal regions without subduction zones (Nelson and Personius, in press). Atwater (1987) and Atwater and Yamaguchi (1991) cite a variety of evidence from Washington marshes that seem to require earthquakes to explain buried marshes. Peterson and Darienzo (in press) have shown that in Alsea Bay, abrupt land subsidence is the only likely cause for the buried marshes observed there. However, the origin of buried layers in other bays may still be questioned.

If we accept that the marshes do subside during earthquakes, we must assess the possibility that each estuary is responding to independent movements on local faults rather than great subduction earthquakes that cause many estuaries to subside at the same time. Goldfinger and others (1990) have studied faults on the continental shelf and slope of Oregon and have identified dozens of major faults which may have moved in geologically recent times. Many of the estuaries where buried marshes occur appear to lie on these faults, raising the possibility of numerous local subsidence events. Further investigation is necessary to determine whether these faults are independently responsible for marsh burial, but several general observations suggest that they are not. First, at least a dozen estuaries between central Oregon and central Washington subsided about 300 years ago (see below). If each subsidence event was the result of an independent earthquake, the implication is that over a dozen occurred in the late 1600s, but none have occurred since the 1840s. There are so many estuaries with relatively recent and frequent marsh burials that we should have historical records of marsh burial events if they are due to random earthquakes on a dozen independent faults. In addition, geologic mapping onshore, in some cases quite detailed, has yet to uncover evidence that any of the offshore faults associated with estuaries has moved in the last few thousand years.

Finally, almost every estuary has evidence of tsunamis associated with one or more of the buried marsh layers. Peterson and Darienzo (in press) have pointed out that if each estuary has an independent earthquake which generates a local tsunami, there will be a tsunami deposit directly above the subsided marsh in that estuary, and tsunami deposits at a variety of levels in adjacent estuaries that did not subside. This implies that tsunami sands should be distributed throughout the peat and intertidal mud layers if there are numerous independent events. On the Oregon coast, Darienzo and Peterson (1988, 1990), Peterson and others (1991), and Peterson (personal communication, 1991) find that the vast majority of tsunami deposits occur directly above buried marshes.

Another unresolved problem with the great subduction earthquake hypothesis is the common occurrence of uplifted marine terraces adjacent to estuaries which contain buried marshes. Sea level has changed dramatically during the last few hundred thousand years, falling during ice ages when water is tied up in glaciers, and rising between ice ages as glaciers melt. During each high stand of sea level, wave action cuts a platform across coastal bedrock, which is then covered by marine sediments to form a distinct, flat marine terrace. The most recent high stand was about 80,000 years ago, and at many sites along the Oregon and Washington coast this terrace is now several meters to tens of meters above modern sea level. If sea level now is about the same as it was 80,000 years ago, these terraces must have been uplifted by earth movements. However, the uplifted terraces are often adjacent to estuaries in which there is clear evidence of several meters of submergence in the last few thousand years. It is necessary to resolve the contradictory evidence for net uplift over the last 80,000 years and net submergence over the last 5,000 to 10,000 years.

A final unresolved problem with the great subduction earthquake hypothesis is the apparent lack of widespread evidence of liquefaction. Liquefaction occurs when loose, water-saturated sand deposits are shaken strongly in an earthquake. The sand becomes fluid, and a mixture of sand and water often erupts onto the ground surface through fissures. These sand fissures and erupted sand piles are commonly observed in many other areas of the world that have been shaken by strong earthquakes. The presence of such features in association with buried marsh horizons would strongly support the great earthquake hypothesis. The widespread absence of liquefaction features along the Oregon and Washington coast could suggest that whatever caused the marshes to subside did not involve strong shaking. Widespread liquefaction features have not been reported from the Oregon coast to date; however, no systematic effort has been made to locate them. In Washington, Atwater (personal communication, 1991)) has found liquefaction features associated with buried marshes at sites on the Copalis River. Peterson (personal communication, 1991) has observed widespread liquefaction on the Oregon coast in marine terrace sediments which are 80,000 years or more old. I have observed similar features in old marine terrace sediments in the Coos Bay area. The critical problem is to find liquefaction features in sediments that are only a few thousand years old. Clearly, a concerted effort must be made to establish whether or not liquefaction features are widespread along the Oregon coast, and if they are not, the great earthquake hypothesis must be carefully re-examined.

When is the Next Big One? The Big Question

If we accept for the time being that buried marsh deposits in Oregon and Washington are natural seismographic records, then the next step is to determine how often, on average, the prehistoric earthquakes occurred. If it is possible to calculate a reliable average time between events, then it is possible to calculate the probability that the next event will occur in some given time frame. This technique has been widely applied in other areas where there is a reasonably well-dated geologic record of prehistoric earthquakes.

The time of burial of marshes in Oregon has been dated by two techniques, each of which has significant drawbacks. Radiocarbon dating can be used to date plant material preserved in the buried marsh or forest peats. The technique is relatively fast and inexpensive, and dateable plant material is abundant. Analytical errors inherent in the technique are typically plus or minus 50 to 100 years, which is not significant for materials that are several thousand years old, but is very significant for materials that are only a few hundred years old. Calibrations for prehistoric variations in radioactive carbon production introduce additional uncertainty, and many relatively young samples correspond to several calendar dates when calibrated. The second source of error is even more of a problem. Radiocarbon ages date the time of death of the plant material, and samples taken from peats may have been dead on the ground for tens or hundreds of years before the marsh subsided. This error can be greatly reduced by dating material from trees rooted in the buried marsh that were presumably killed by the subsidence, but such trees are far less common than peats. In general, at any site, it may not be possible to date the time of marsh subsidence any closer than plus or minus 100 to 200 years. This means that we cannot necessarily distinguish between events that occurred a day apart and events that occurred a few hundred years apart, and it may well be that the average time between earthquakes is similar to or smaller than the best resolution of radiocarbon dating.

The second dating technique is tree-ring dating, which is accomplished by comparing the patterns of annual growth rings in trees killed by subsidence to those in living trees on adjacent uplands. This technique allows dating of the time of death of the trees to within a decade, or often within a few years (Atwater and Yamaguchi 1991). However, well-preserved trees are not present in many sites, and living trees are not old enough to compare with buried marshes that are more than 1,000 years old. This technique is most useful for looking at the most recent events.

A final problem in calculating the average time between earthquakes is the possibility that due to conditions of sedimentation, timing, local climate, sea level fluctuations, and so on, not all earthquakes will make unambiguous buried marsh horizons at all sites. This means that recurrence intervals estimated for any one site will be based on a minimum number of events thought to have occurred. If one or two events were not clearly recorded, then the resultant estimate of recurrence interval will underestimate the probability of the next earthquake.

The uncertainties associated with dating marsh subsidence mean that a credible calculation of the probability of the next earthquake is still not possible, even assuming that buried marshes represent past earthquakes. The best we can do with the radiocarbon numbers at this point is to take the reported ages at face value and treat the resulting estimates of recurrence intervals with a great deal of skepticism. An important result we can derive from this kind of analysis is not so much which day to be out of town in order to avoid the Big One, but a sense of how short an interval is possible between great earthquakes, and a reasonable estimate of when the last one occurred.

The most recent event is probably the best dated, because it is best exposed and because locally the radiocarbon dating can be checked with tree-ring dating of cedar and spruce trees killed by marsh subsidence. Atwater and Yamaguchi (1991) find that in southwest Washington, radiocarbon and tree-ring dating suggest that the most recent subsidence occurred about 300 years ago. Peterson and others (1991) report a range of ages for the most recent event in Oregon bays, with the youngest at 270, plus or minus 60 and the oldest at 550, plus or minus 70 years BP. Grant (written communication, 1991) reports the most recent subsidence in the Salmon River of 247, plus or minus 25 years BP, and in the Nehalem River, 225, plus or minus 19 years BP. Adams (1990) estimated the age of the most recent turbidite offshore at 300 years BP by studying the thickness of sediment layers on top of the turbidite. Most of these dates are consistent with the more precise tree-ring data indicating that the last great event or set of events occurred in the late 1600s, but it is not possible to distinguish between one great simultaneous event and several smaller events scattered over decades.

The average intervals between earthquakes calculated from this data must be treated skeptically. Atwater (personal communication, 1991) is not sure that a significant return time can be calculated, but points out that there have been either 6 or 7 events in the last 3,500 years. This suggests a nominal recurrence of 500 to 580 years. Peterson and others (1991) report average intervals of 370 years for 4 events at Netarts Bay, 340 years for 3 intervals in Alsea Bay, and a regional average over 11 events in Northern Oregon of 330 to 340 years. Adams calculated an average of 590 years for 13 events, using the turbidite data. There is wide variability in this data, but two things are clear. If all of these events were due to independent earthquakes on local structures, then there have been tens of earthquakes in the last few thousand years. The return interval between subsidence-causing earthquakes somewhere along the coast then becomes so short that we would expect to have a historical record of one. The other important fact to note is that recurrence intervals from many sites are at least as short as the time since the last event, within the limits of radiocarbon error.

We have a long way to go before we can quantify the likelihood of the next great earthquake, but this event is not necessarily going to occur in some remote future. In fact, it is quite possible that the next big shake will happen in the near future. This possibility should be sufficient to cause emergency managers, land-use planners, and public officials of coastal communities to start looking at where they are vulnerable.

Where and How Big: What Can We Expect?

Estimates of the size and potential location of future great subduction earthquakes also vary widely and are based on a limited understanding of the structure of the CSZ. The size of future earthquakes will depend on the area of the locked fault between the plates that moves. The location of the earthquake will similarly depend on the portion of the fault that moves.

The area of the fault that moves depends on the width of the locked portion of the fault and the length of fault along the coast that fails. The total length of the CSZ is fairly well known, but few researchers think that the entire 1000 km will fail all at once. Instead, the CSZ is likely to break in a series of relatively short segments. Geoscientists can guess at the location of segment boundaries but still cannot demonstrate where they lie. Segments may be as short as 100 kilometers or the full 1,000 kilometers. Similarly, the width of the locked portion of the fault strongly influences the possible size of an earthquake. The location of the locked zone also controls where the earthquakes can occur. There is little agreement on the likely width of the locked zone. In southern Oregon, Clark and Carver (1991) proposed that the locked zone might be as wide as 75 to 100 kilometers in southern Oregon. Peterson and others (1991) present a model of the locked zone constrained by marsh subsidence data that is best fit by a 90-kilometer-wide locked zone. Blackwell (1991) proposes a locked zone as narrow as 20 kilometers based on thermal modelling. According to Pezzopane and others (1991), geodetic data suggests that it may vary widely in width. A pair of potential locked zones is shown in figure 12.

portion of the coast around Newport to illustrate specific potential hazard zones (figures 13 and 14). DOGAMI has published environmental geology maps of almost all of the coast of Oregon.

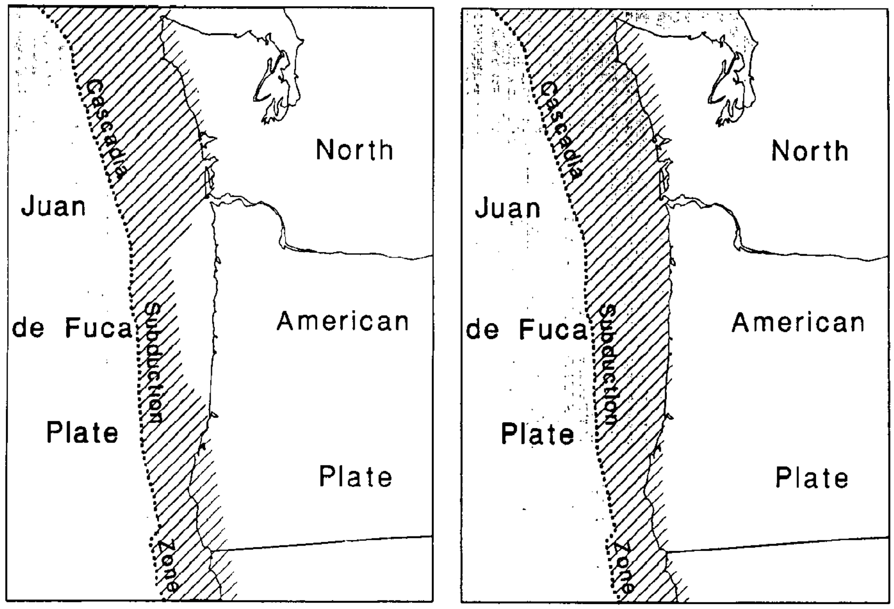


Figure 12. Example source zones for hypothetical subduction earthquakes. Example on right after Pezzopane and others, 1991. Example on left after Weaver and Shedlock, 1989.

Using this range of possible lengths and widths of rupture zone, researchers have suggested maximum CSZ earthquakes of from Mw 8.0 (Pezzopane and others 1991) to 9.1 (Rogers 1988). Similarly, the portion of the fault that fails may either be entirely offshore or extend a few tens of kilometers onshore. In any case, coastal Oregon will be uncomfortably close to any CSZ earthquake, and even the most distant possible earthquake of the smallest likely size (8.0) will cause significant shaking and damage.

Effects of Great Earthquakes: Shake, Rattle, Roll, Slide, Slosh, and Slump

How would a major earthquake affect the Oregon Coast? We still know too little about the potential size and location of earthquakes to make quantitative estimates of the kinds of damage that might occur, but we can provide gross estimates. Damaging effects of earthquakes fall into two categories: (1) the direct effects of ground shaking, fault rupture, and coseismic subsidence and (2) the secondary effects of tsunami, seiche, settlement, liquefaction, and landsliding. In this section, I describe the potential impact of each of these hazards on the Oregon coast, using a

These maps can be used by trained professionals to make a first-order assessment of potential earthquake hazards. For this report, the maps are out of Bulletin 81, *Environmental Geology of Lincoln County* (Schlicker and others 1973).

Ground Shaking and Amplification

The most widely experienced effect of an earthquake is ground shaking, which is also typically responsible for the majority of earthquake damage. The strength of shaking at any site during an earthquake will depend on the size of the earthquake, the distance of the site from the epicenter, and the nature of the geologic materials under the site. Larger earthquakes produce stronger ground shaking, but the strength of shaking dies off rapidly with distance from the epicenter. To predict the strength of shaking at a given site, we need to know how large the earthquake will be and where it will be centered, both currently impossible to know. A few general models of the strength of ground shaking have been made for the Oregon coast. The strength of ground shaking is usually expressed as a fraction of the force of gravity. Levels above .2 acceleration of gravity (g) are significant, and modern buildings in Oregon are designed for .2 g. Pezzopane and others

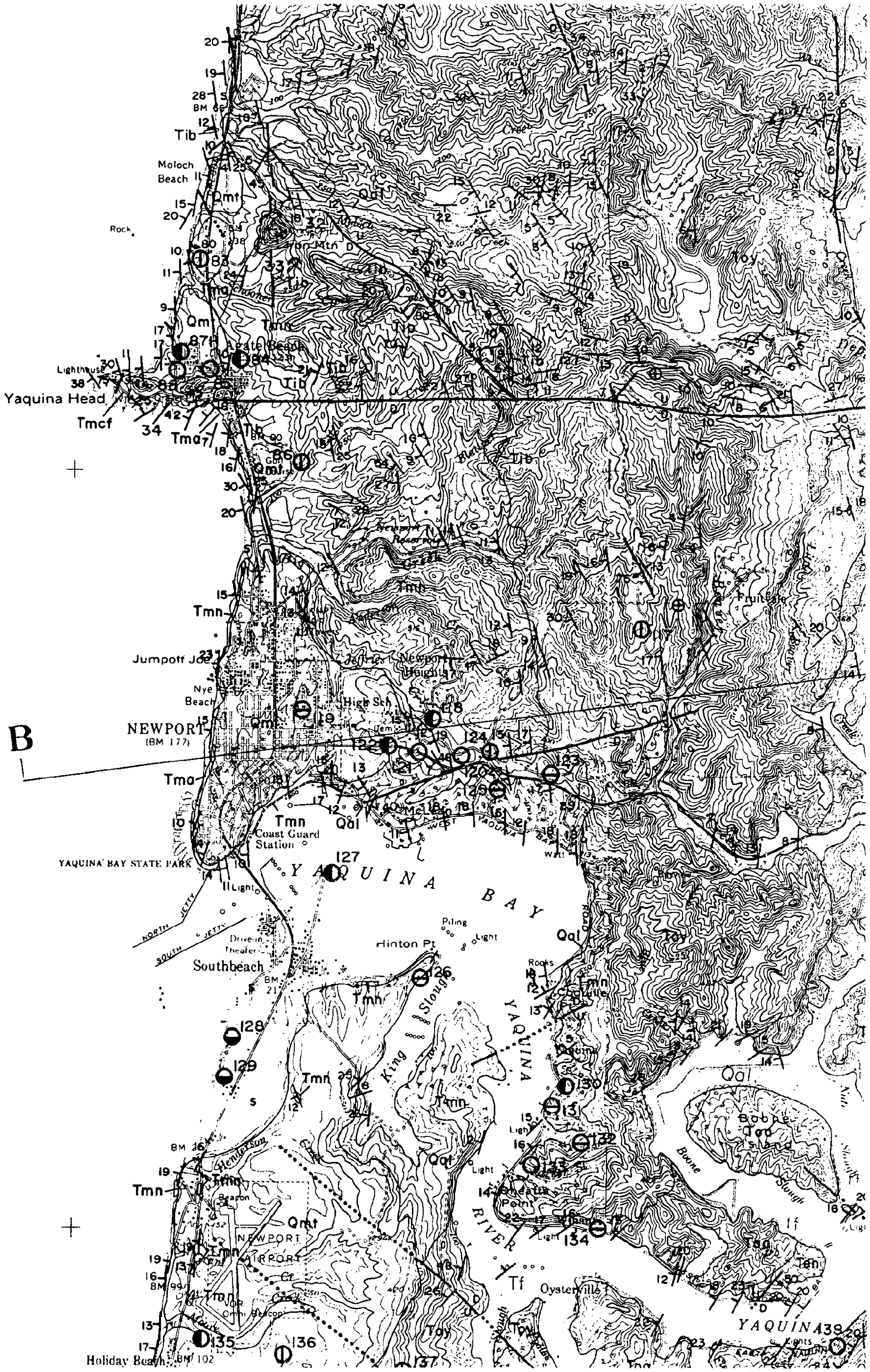


Figure 13. Geologic map of the Newport area, Lincoln County, Oregon. After Schlicker and others, 1973.

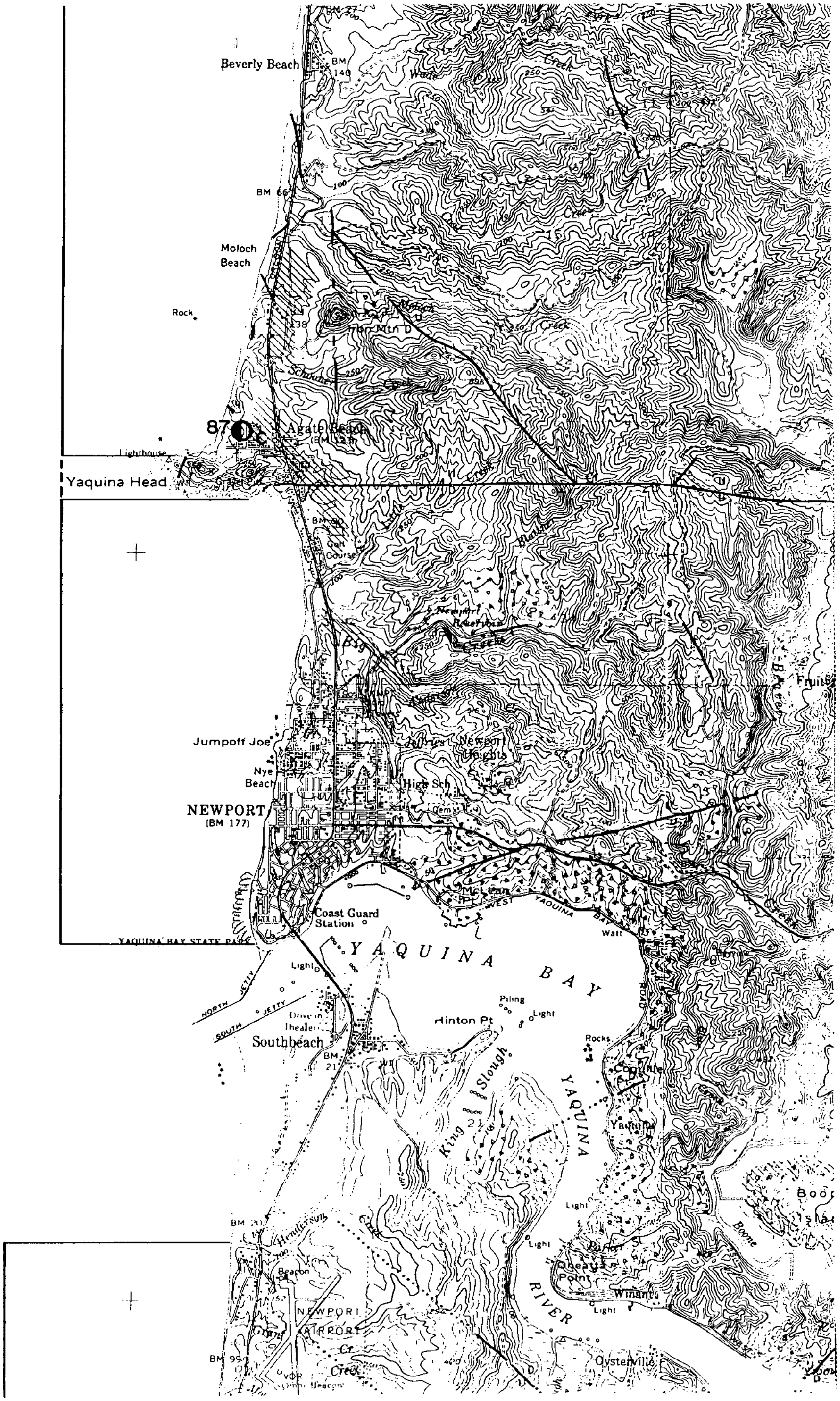


Figure 14. Environmental Geology map of the Newport area, Lincoln County, Oregon. After Schlicker and others, 1973.

(1991) suggest that peak horizontal accelerations of .2 g to .4 g can occur along the coast. Cohee and others (1991) model a magnitude 8.1 subduction zone earthquake and suggest that coastal Oregon might experience .14 g to .41 g of peak horizontal acceleration. An additional threat unique to CSZ earthquakes is the unusually long duration of shaking. The magnitude (Mw) 8.1 earthquake modelled by Cohee and others (1991) would cause strong shaking for over 45 seconds. Damage increases dramatically as the duration of shaking increases.

The ground motion levels discussed above are for bedrock sites. The presence of thick soils, alluvial deposits, or soft rock over the bedrock can greatly amplify the ground shaking, often by factors as high as six. In general, young (Quaternary) deposits of sand, silt, and clay are most likely to amplify ground shaking, although less frequently they may actually reduce ground shaking. Figure 15 is derived from figure 13, the geologic map from DOGAMI Bulletin 91, and shows the areas covered by the geologic units labelled Qmt (Quaternary Miocene terrace) and Qal (Quaternary alluvium). The Qmt deposits are young marine terrace sand deposits, and the Qal deposits are young sand, silt, and gravel deposits lining the bays and river valleys. These units are most likely to amplify shaking, in contrast to the bedrock deposits present in the rest of the area. Therefore, for a preliminary assessment, these areas would be considered more potentially hazardous, and more refined hazard assessments would be focused there. The actual threat of amplification can be modeled by computer techniques for a given site, a procedure that might be appropriate for large structures or critical facilities like hospitals.

To illustrate the importance of soil amplification, we can look at the Mexico City earthquake of 1985. This earthquake, a magnitude (Mw) 8.1 subduction zone megathrust event, was centered 300 kilometers from Mexico City. Soft alluvium in the old lake beds on which the city is built amplified the shaking sufficiently to cause complete collapse of numerous modern structures engineered to withstand earthquakes. Similarly, the portion of the Cypress Freeway structure that collapsed in the 1989 Loma Prieta earthquake was only that part built on soft bay mud.

Coseismic Subsidence

As we saw earlier, the footprint that a great subduction earthquake makes on the land is a pattern of rapid subsidence or uplift of the land. This movement, which takes place during the earthquake, is called coseismic movement. It is the occurrence of coseismic subsidence along the Oregon coast that is thought to be responsible for the repeated burial of marshes, and a future great subduction earthquake would be likely to produce similar effects. It is possible to estimate the amount of coseismic subsidence at a marsh site by identifying the ecological zones represented by the successive layers and measuring the difference in elevation between modern representatives of those zones. Peterson and others (1991) have made such estimates of the average coseismic subsidence at three bays for the last four burial events. They found 1.0 to 1.5 meters of subsidence at Netarts Bay, .5 meter to 1.5 meters at Alsea Bay, and 0 to .5 meter at the Siuslaw River. These are not dramatic amounts of subsidence and are unlikely to cause large-scale flooding of coastal communities. However, this subsidence adds to the flooding by the subsequent tsunami and causes increased flooding during storms and accelerated coastal erosion.

Fault Rupture

As discussed in the section on crustal earthquakes, we know of few young faults on the coast of Oregon. However, there are numerous offshore faults. These offshore faults appear to cut the seafloor and are therefore likely to have moved in geologically recent times. Ground rupture caused by movement of an offshore fault is not a great problem because there is no development offshore. Figure 16, derived from the geologic map in figure 13, shows several major west-northwest trending faults passing south of Yaquina Bay. These faults are very similar in trend to the geologically young offshore faults, and there remains a possibility that they may move during a great subduction earthquake or independently in a smaller crustal earthquake. The likelihood is probably remote, so again, this hazard might be of concern only in the siting and construction of critical structures. It is very expensive to engineer structures to tolerate fault rupture beneath their

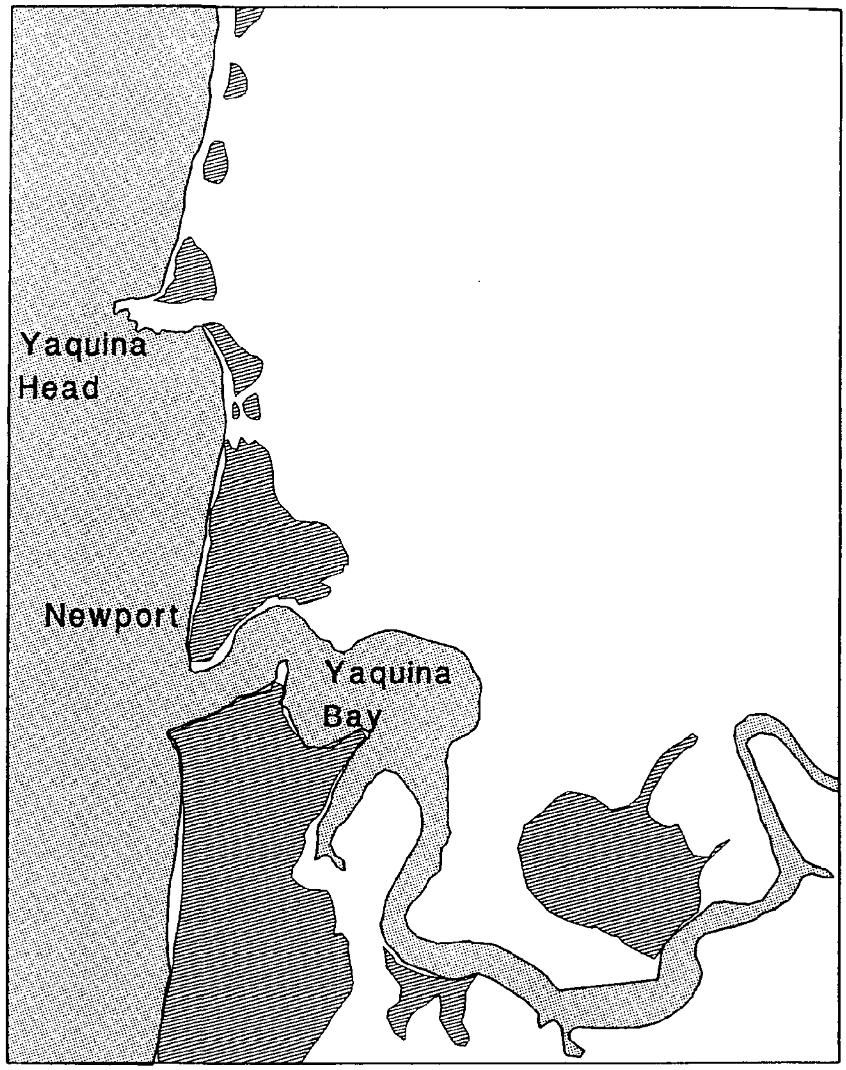


Figure 15. Example amplification opportunity map. Hatched areas are likely to shake most strongly in an earthquake because of loose Quaternary deposits.

foundations, but it is relatively easy to site structures well away from the potential rupture zone.

Liquefaction and Settlement

Many geologically young sand and silt deposits are relatively loose, meaning that the sand particles are not tightly packed together and there are significant spaces between grains. When shaken by an earthquake, loose sand or silt can become more compact, just as flour settles when shaken in a measuring cup. If the sand is dry, ground settlement occurs, which may locally be sufficient to damage structures. An even more destructive situation exists when the sand is saturated with water before the earthquake. The settlement of the sand pressurizes the water in the spaces between grains, and the pressurized water causes the sediment to liquefy. Because liquefied sediment has very little strength, it is common for structures to tilt, sink or settle dramatically when the underlying soil liquefies. Even more devastating is the tendency for liquefied soil to flow towards free faces (such as river or bay banks) and down very gentle slopes. Mass movement of liquefied or partly liquefied soils results in the most spectacular of earthquake damage and is particularly devastating to coastal areas, damaging bridges, docks, and port facilities. Liquefaction also causes widespread failure of buried pipes and cables, affecting fire fighting and emergency communications after the event.

As with amplification, the tendency of any site to liquefy in an earthquake can be estimated accurately only with a detailed site-specific study. The Qmt and Qal deposits are the only geologic materials in this area with any significant potential for liquefaction. Although they are widespread, these materials pose a threat only where they are

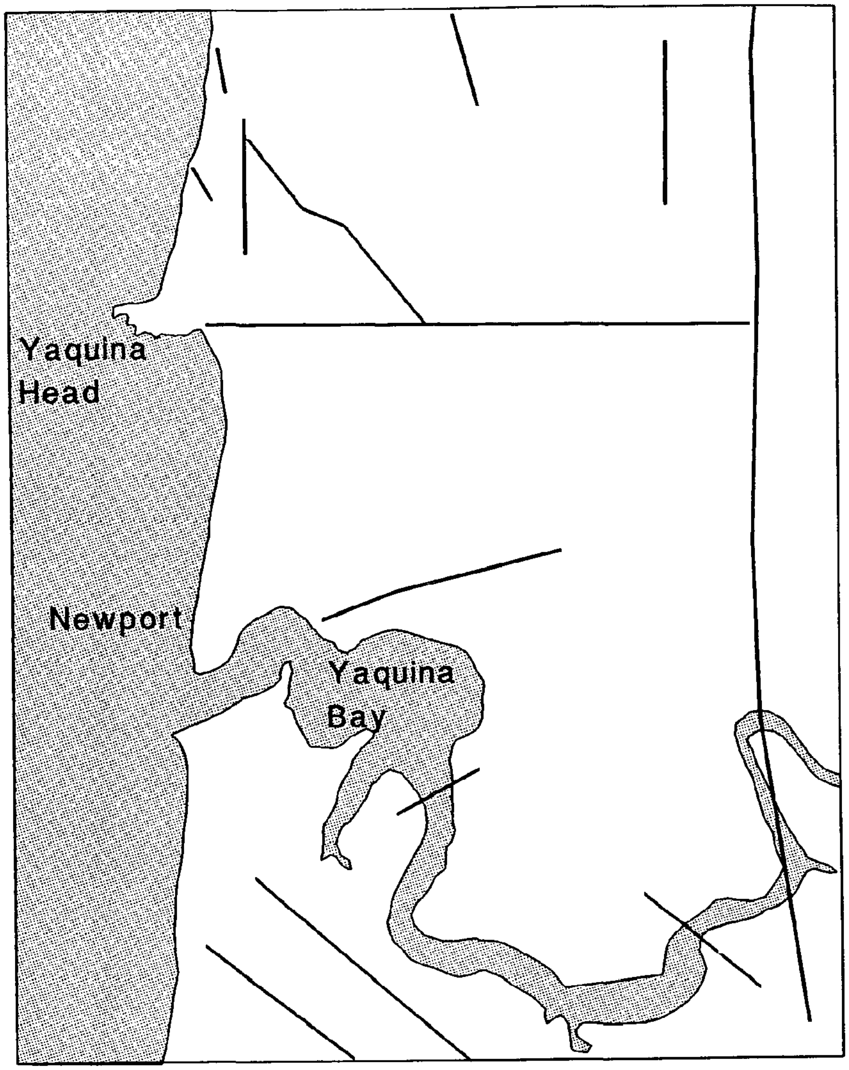


Figure 16. Example fault rupture opportunity map. Heavy lines are mapped faults.

saturated with groundwater. Again, we can use the geology and environmental hazard maps for the Newport area to roughly estimate the areas most susceptible to liquefaction, and thus narrow down the area where more specific studies are needed. Figure 17 shows areas likely to be susceptible to liquefaction. It is derived by overlaying areas of shallow ground water (depicted on the environmental geology map, figure 14) on areas of Qmt or Qal sands and silts (depicted on the geologic map, figure 13).

Landslides

One of the most common secondary hazards associated with earthquakes is earthquake-induced landslides. Slopes which are stable under ordinary conditions may be destabilized by the strong shaking of an earthquake and begin to move. Wilson and Keefer (1985) note that earthquake-induced landslides can occur up to 200 kilometers from the epicenter of a magnitude 8 earthquake. As with the amplification and liquefaction hazards, detailed site studies are required to determine how likely a slope is to slide in the event of a given earthquake. Again, it is possible to use the information available in the DOGAMI environmental hazard maps to outline areas most likely to experience this hazard. Figure 18 shows two types of landslide data derived from the maps. Areas of existing landslides or landslide topography are taken directly from the environmental geology map (figure 14). These areas may be reactivated in future earthquakes, particularly where they have been developed, cut by roads, or logged. Landslide-prone areas are derived by overlaying areas of mudstone bedrock from the geologic map (figure 13) on areas with slopes over 25% from the environmental geology

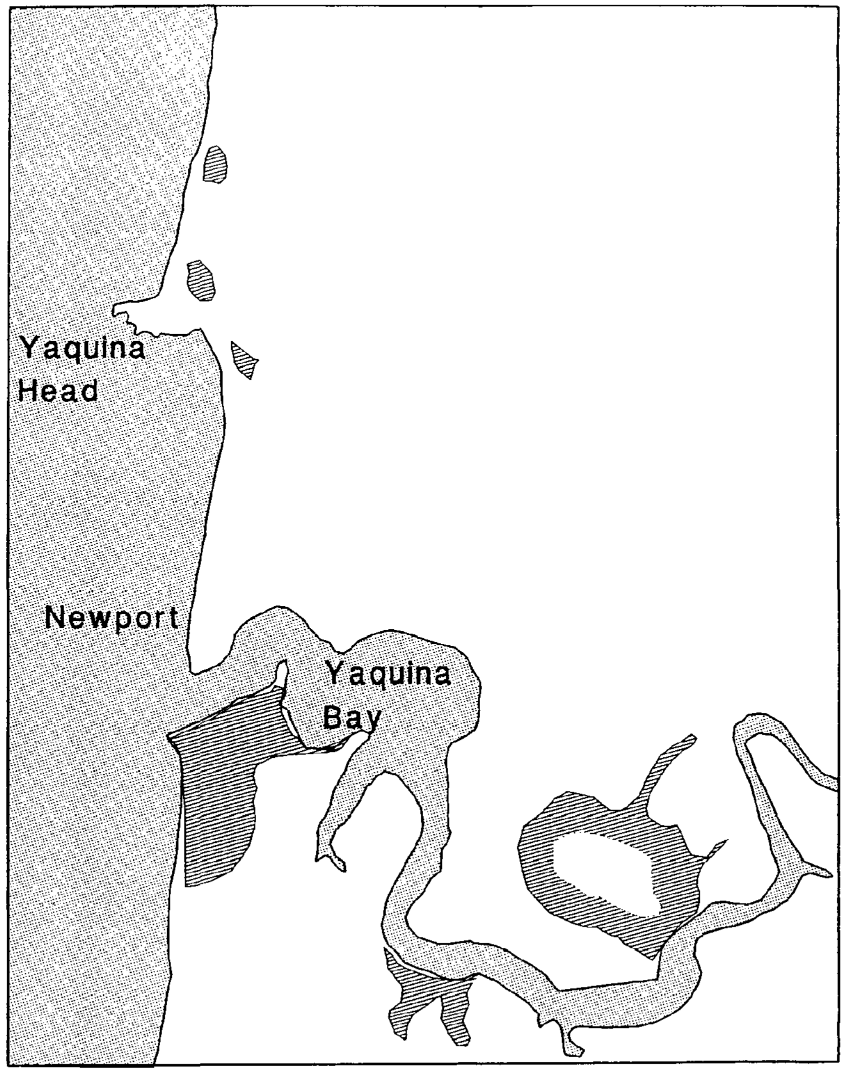


Figure 17. Example liquefaction opportunity map. Hatched zones have both loose sands and shallow groundwater.

map (figure 14). These areas are the most likely to have new landslides in an earthquake. In addition, areas of rapid sea cliff erosion or riverbank erosion may be susceptible to earthquake-induced landsliding. In all cases, extensive development, logging, forest fires, or road building may increase the likelihood of earthquake-induced landslides because of changes in drainage and stability of the slopes.

Tsunami and Seiche

The final class of secondary earthquake hazard is mass movements of water which may inundate shoreline areas. In a seiche, the water in a relatively small body of water, like a lake or bay, sloshes from bank to bank, just like a full coffee cup on a bumped table. A tsunami occurs when a large area of the seafloor moves, displacing a huge amount of water in the ocean. Both of these hazards are likely to occur in the event of a subduction zone earthquake, but only seiches are likely to occur in a crustal or intraplate earthquake.

The extent of inundation caused by a seiche in any body of water will depend on the strength of ground shaking at the site. It will also depend on the degree of similarity between the natural period of oscillation of the body of water and the period of shaking of the earthquake. This makes estimation of seiche hazards extremely difficult, because the periods of shaking of earthquakes are quite variable. Sophisticated computer modelling can put rough limits on the maximum seiche run-up, but this technique is relatively expensive.

Tsunamis are great waves produced by vertical motion of large portions of the seafloor. The waves travel at speeds of several hundred kilometers per hour in the open ocean, where they may

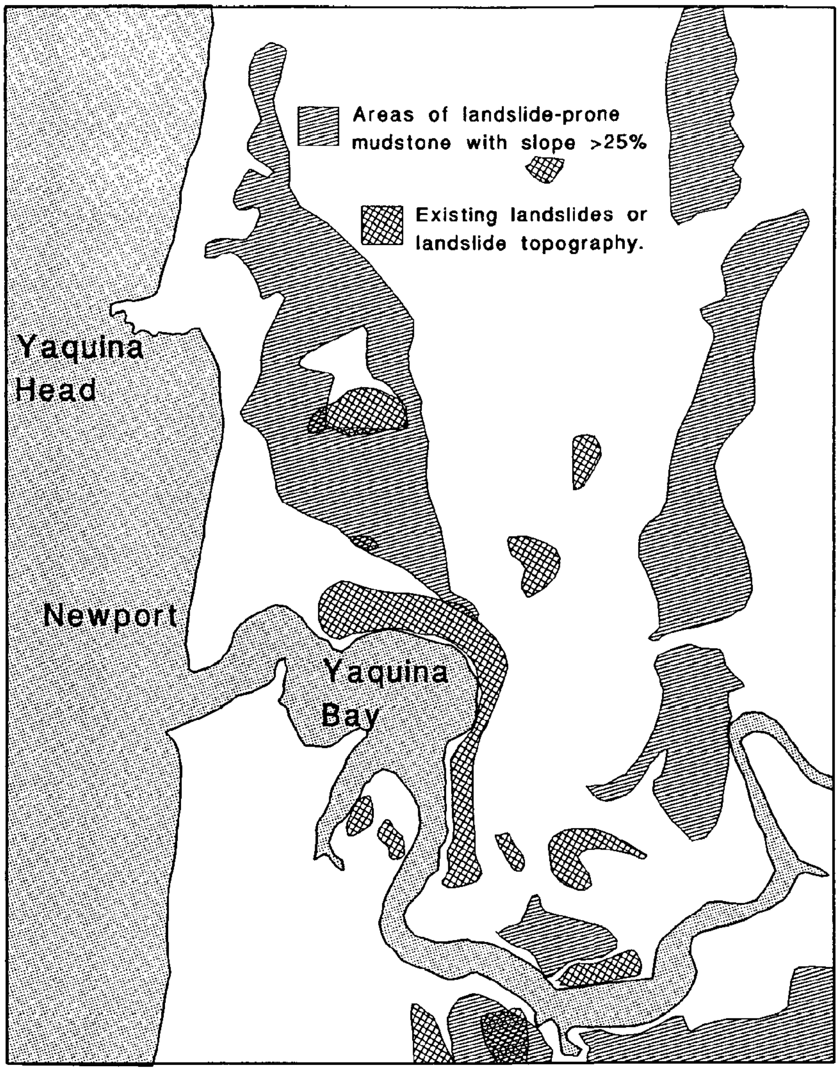


Figure 18. Example earthquake-induced landslide opportunity map.

be only a fraction of a meter high. When a tsunami wave approaches shore, it begins to slow down and get higher, and what began as a wave only a half a meter high on the open ocean may be several meters high when it reaches shore. The maximum elevation above sea level that the tsunami reaches is called the run-up. The area covered by the tsunami is the inundation. Tsunamis are not likely to be generated by crustal or intraplate earthquakes, because these types of earthquakes are relatively small and do not involve vertical movements of the seafloor. Subduction zone earthquakes, on the other hand, are very large, cause large vertical movements of the seafloor, and usually cause tsunamis. There is currently a warning system in place to alert residents of the Oregon coast to the approach of tsunamis generated in Alaskan, Chilean, or Japanese subduction zones, but the tsunami generated by an earthquake on the CSZ would arrive without any warning other than the earthquake itself.

Without knowing the exact size and location of future subduction zone earthquakes, it is difficult to predict tsunami run-up heights for the Oregon coast. There are, however, several crude approaches available to get a general feel for the possible magnitude of locally generated tsunamis. The first approach is to look at the "tsunami" sand deposits associated with buried marshes along the coast. This has been done by Peterson and others (1991a), who produced maps of the areas thought to have been inundated by the tsunamis that followed past subduction earthquakes. Unfortunately, all the tsunami deposits are preserved in the modern estuaries, so these maps show only the minimum area covered by the tsunami. Tsunami sands are not preserved if they are deposited on slopes above the bay, so we cannot use this technique to determine the maximum water level, only the minimum. Peterson and others (1991a) found prehistoric tsunami sands at least 2 kilometers (and possibly 18 kilometers) up Yaquina Bay.

The other approaches to tsunami height is computer modeling. The modeling of waves traveling in water is fairly straightforward, but it is extremely complex to model how the wave behaves when it enters shallow water (less than 50 meters) and interacts with the irregular floor of the shallow sea. It is even more complicated to model how the wave behaves in estuaries. Two attempts have been made to model a locally generated tsunami caused by a subduction zone earthquake. Hebenstreit (1988) modeled the tsunami likely to accompany a magnitude 9.1 (Mw) earthquake (figure 19). His model shows expected wave height along the Oregon coast at points a few kilometers offshore, thereby sidestepping the shallow-water problem. Clearly, these wave heights, locally as much as 12 meters, represent a serious threat. Baptista and others (1991) have produced a simple model as a prelude to a more complete model. Their initial model is designed to test the sensitivity of tsunami height to various factors and only estimates tsunami height at the latitude of Astoria. Again, this model gives wave height only at a water depth of 50 meters and does not carry the wave onshore. The Baptista and others model suggests that a wave about 7 meters high would be likely from an average subduction zone earthquake. The wave height in this model is very dependent on variables that are still poorly known, so the wave height may not be reliable. The arrival time of the tsunami is much less variable, however, and underscores the unique threat associated with locally generated tsunamis. The tsunami crest in the model reaches the coast 20 to 30 minutes after the earthquake. This is not enough time for an official warning to be issued, so all coastal residents should consider strong ground shaking as a natural tsunami warning and should seek high ground immediately.

The actual height above sea level reached by any tsunami will depend on many local factors, including the offshore wave height, the shape of the shore or estuary, the normal tidal stage at the time, and the amount of coseismic subsidence. It is not unreasonable for many parts of the Oregon coast to expect tsunami run-up of 5 to 10 meters, with inundation extending several kilometers up many estuaries.

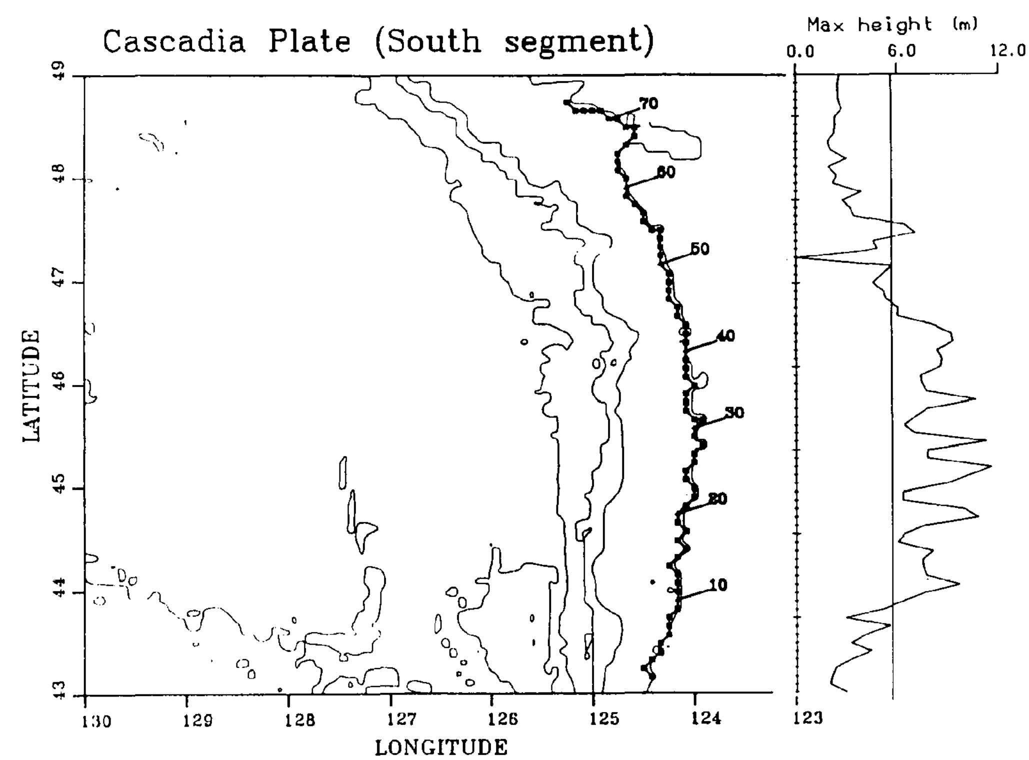


Figure 19. Computer model of local tsunami in the Pacific Northwest from a hypothetical Mw 9.1 subduction earthquake. Right hand figure shows the pattern of wave elevation for all recording points; the solid line is the average for all points. Wave heights are for points offshore; they cannot be used to estimate coastal run-up or inundation. From Hebenstreit, 1988.

Conclusions: Should We All Move to Nebraska?

Where does all of this uncertain science leave the residents and decision makers of Oregon's coastal communities? Some may think that we must evacuate the coast forever; others will think we can continue to develop without regard to seismic hazards. The truth, of course, lies in between. Let's look at a few key facts.

- In 150 years or so of our history, there has been no earthquake damage on the coast, yet there has been abundant damage caused by mundane hazards like storms, coastal erosion, and landslides.

- The best geologic data now available strongly suggests, but cannot prove, that most of the coast is susceptible to large damaging earthquakes. These events are certainly rare on human time scales, but could occur at any time.

- The natural geologic makeup of the coast makes it prone to a variety of earthquake hazards, and any large earthquake is likely to cause a large amount of damage.

- It is possible now to make a broad assessment of hazard zones in which individual sites need to be investigated in more detail.

- Lifelines in Oregon coastal communities are likely to be severely impaired in the event of large earthquakes, affecting emergency response operations.

- The long-term economic impact of a large earthquake may destroy communities more thoroughly than the ground shaking.

- No community can afford to "earthquake proof" all of its lifelines and economic infrastructure in the short run.

What should be done, given these facts? Certainly we need more research to answer many of the uncertainties about the earthquake threat, but we know enough to begin to act. Earthquake hazards can be reduced in communities by increasing public awareness of the hazard and by protecting lifelines and structures. The first is relatively inexpensive, and can save many lives. Community groups, the Red Cross, and others can help to educate the community about earthquake and general disaster preparedness. Protecting the infrastructure is economical over the long run, as long as it is integrated into long-range building and land-use plans. Hazardous buildings will probably not get fixed, but they should be replaced by earthquake-resistant structures when their natural life is over. Similarly, facilities sited in hazard zones probably won't get moved, but their replacements should be sited properly. Planning carefully, identifying hazard zones, and considering potential earthquake safety as an element in any development project will lead in the long run to a much more earthquake-resistant Oregon coast. Odds are that we have decades to prepare. We should not squander that opportunity.

References

Adams, J., 1984, Active deformation of the Pacific Northwest continental margin: Tectonics 3:449-472.

Adams, J., 1990, Paleoseismicity of the Cascadia subduction zone: Evidence from turbidites off the Oregon-Washington margin: Tectonics 9:569-583.

Ando, M., and Balazs, E.I., 1979, Geodetic evidence for aseismic subduction of the Juan de Fuca plate: Journal of Geophysical Research 84:3023-3027.

Atwater, B.F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: Science 237:942-944.

Atwater, B.F., 1989, Geologic studies for seismic zonation of the Puget Sound lowland. U.S. Geological Survey Open-File Report 89-453, p 520.

Atwater, B.F., and Yamaguchi, D.K., 1991, Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington State: Geology 19:706-709.

Baptista, A.M., Remedio, J.M., and Peterson, C.D., 1991, Sensitivity Analysis to tsunami propagation on the Pacific Northwest coast:

final technical progress report to the Oregon Department of Geology and Mineral Industries, Portland, Oregon.

Blackwell, D., 1991, Oral presentation at 2nd workshop on Oregon earthquake sources, Corvallis, Oregon, April 18, 1991.

Byrne, D.E., Davis, D.M., and Sykes, L.R., 1988, Loci and maximum size of thrust earthquakes and the mechanics of the shallow region of subduction zones: Tectonics 7:833-857.

Carver, G.A., 1991, Oral presentation at 2nd workshop on Oregon earthquake sources, Corvallis, Oregon, April 18, 1991.

Clark, S.H., and Carver, G.A., 1991, Oral presentation at 2nd workshop on Oregon earthquake sources, Corvallis, Oregon, April 18, 1991.

Cohee, B.P., Somerville, P.G., and Abrahamson, N.A., 1990, Simulated ground motions for hypothesized Mw 8 subduction earthquakes in Washington and Oregon: Bulletin of the Seismological Society of America, Vol. 81, No. 1.

Darienzo, M.E., and Peterson, C.D., 1988, Coastal Neotectonic field trip guide for Netarts Bay, Oregon: Oregon Geology 50:99-106.

Darienzo, M.E., and Peterson, C.D., 1990, Episodic tectonic subsidence of late Holocene salt marshes, Northern Oregon central Cascadia margin: Tectonics 9:1-22.

Goldfinger, C., Mackay, M.C., Kulm, L.D., and Yeats, R.S., 1990, Neotectonics and possible segmentation of the Juan De Fuca plate and Cascadia subduction zone off central Oregon: EOS, Transactions of the American Geophysical Union 71:1580.

Grant, W.C., and McLaren, D.D., 1987, Evidence for Holocene subduction earthquakes along the Northern Oregon coast: EOS 68:1239.

Griggs, G.B., and Kulm, L.D., 1970, Sedimentation on the Cascadia deep-sea channel: Geological Society of America Bulletin 81:1361-1384.

Harbert, W., 1991, Late Neogene relative motions of the Pacific and North America plates: Tectonics 10:1-15.

Heaton, T.H., and Kanamori, H., 1984, Seismic potential associated with subduction in the northwestern United States: Bulletin of the Seismological Society of America 74:933-941.

Heaton, T.H., and Snavely, P.D., Jr., 1985, Possible tsunami along the northwestern coast of the United States inferred from Indian traditions. Bulletin of the Seismological Society of America 75:1455-1460.

Hebenstreit, G.T., 1988, Local Tsunami hazard assessment for the Juan de Fuca plate area: Report to U.S. Geological Survey, Contract 14-08-001-G1346, by Science Applications International Corporation, McLean VA.

Jacobson, R.S., 1986, Map of Oregon Seismicity, 1841-1986: State of Oregon Department of Geology and Mineral Industries GMS 49.

Johnson, A.G., and Scofield, D.H., 1991, Reassessment of the seismic hazard for the State of Oregon: Preliminary report to the Oregon Department of Geology and Mineral Industries (DOGAMI).

Ludwin, R.S., Weaver, C.S., and Crosson, R.S., 1989, Seismicity of Oregon and Washington: In Slemmons, D.B., Engdahl, E.R., Blackwell, D., Schwartz, D., and Zoback, M., eds. Neotectonics of North America, Geological Society of America Decade of North American Geology, Volume GSMV-1. (Preprint).

McInelly, G.W., and Kelsey, H.M., 1990, Later Quaternary, tectonic deformation in the Cape Arago-Bandon region of coastal Oregon as deduced from wave-cut platforms: Journal of Geophysical Research 95:6699-6713.

Nelson, A.R., and Personius, S.P., in press. The potential for great earthquakes in Oregon and Washington: an overview of recent coastal geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia subduction zone; From A.M. Rogers, W.J. Kockelman, G. Priest, and T.J. Walsh, eds., Assessing and reducing earthquake hazards in the Pacific Northwest, U.S. Geological Survey Professional Paper.

Noson, L.L., Qamar, A., and Thorsen, G.W., 1988, Washington State Earthquake Hazards: Washington Division of Geology and Earth Resources Information Circular 85.

Peterson, C.D., and Darienzo, M.E., 1988, Coastal Neotectonic Field trip guide for Netarts Bay, Oregon: Oregon Geology 50:99-106.

Peterson, C.D., and Darienzo, M.E., in press. Discrimination of climatic, oceanic and tectonic forcing of marsh burial events from

Alsea Bay, Oregon, U.S.A.: From A.M. Rogers, W.J. Kockelman, G. Priest, and T.J. Walsh, eds., Assessing and reducing earthquake hazards in the Pacific Northwest, U.S. Geological Survey Professional Paper.

Peterson, C.D., Darienzo, M.E., and Clough, C., 1991, Recurrence intervals of coseismic subsidence events in Northern Oregon bays of the Cascadia margin. Final Technical Report to the Oregon Department of Geology and Mineral Industries (DOGAMI), September 9, 1991.

Peterson. C.D., Baptista, A.M., and Darienzo, M.E., 1991a, Paleo-Tsunami evidence in northern Oregon bays of the central Cascadia margin: Final Technical Progress Report to the Oregon Department of Geology and Mineral Industries, Portland, Oregon.

Pezzopane, S.K., Weldon, R.J., Johnson, A.G., and Scofield, D.H., 1991, Seismic Acceleration maps from Quaternary Faults and Historic Seismicity in Oregon: Final technical progress report to the Oregon Department of Geology and Mineral Industries, Portland, Oregon.

Plafker, G., 1972, Alaskan Earthquake of 1964 and Chilean Earthquake of 1960: Implications for Arc Tectonics: Journal of Geophysical Research 77:901-925.

Riddihough, R., 1984, Recent movements of the Juan de Fuca plate system: Journal of Geophysical Research, 89:6980-6994.

Rogers, G.C., 1988, An assessment of the megathrust earthquake potential of the Cascadia subduction zone: Canadian Journal of Earth Sciences 25:844-852.

Savage, J.C., and Lisowski, M., 1991, Strain measurements and potential for a great subduction earthquake off Oregon and Washington: Science 252:101-103.

Schlicker, H.G., Deacon, R.J., Beaulieu, J.D., and Olcott, G.W., 1973, Environmental Geology of Lincoln County, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 81.

Vincent, P., 1989, Geodetic deformation of the Oregon Cascadia margin: (M.S. Thesis) Eugene, Oregon, University of Oregon.

Weaver, C.S., and Baker, G.E., 1988, Geometry of the Juan de Fuca Plate beneath Washington and Northern Oregon from seismicity: Bulletin of the Seismological Society of America 78:264-275.

Weaver, C.S., and Shedlock, K.M., 1989, Potential subduction, probable intraplate and known crustal earthquake source areas in the Cascadia subduction zone: In W.W. Hays, ed. Proceedings of Conference XLVIII, 3rd Annual Workshop on Earthquake Hazards in the Puget Sound, Portland Area. U.S. Geological Survey Open File Report 89-465.

Weldon, R.J., 1991, Active tectonic studies in the United States, 1987-1990: In U.S. National Report to International Union of Geodesy and Geophysics 1987-1990, Contributions in Geophysics, American Geophysical Union, pp. 890-906.

Wilson, R.C., and Keefer, D.K., 1985, Predicting areal limits of earthquake-induced landsliding: In J.I. Ziony, ed. Evaluating earthquake hazards in the Los Angeles Region-An earth science perspective. U.S. Geological Survey Professional Paper 1360.

Woodward, J., 1990, Palcoseismicity and the archaeological record: Areas of investigation on the northern Oregon coast: Oregon Geology 52:57-65.

SCIENCE

SEISMIC HAZARDS ON THE OREGON COAST—A RESPONSE

Richard W. Rinne
RZA Engineers, Portland, Oregon

PACIFIC NORTHWEST COASTAL EARTHQUAKE, TSUNAMI, AND LANDSLIDE HAZARDS

I am going to limit my discussion to things that I actually have knowledge of, namely landsliding.

In my opinion, landsliding holds the most potential for liability and is the most visible hazard along the Oregon coast, especially between Newport and Lincoln City. This is not to say that landsliding is confined to this portion of the coast; rather, it is one of the most populated areas and subjected to more human activity than most other areas.

Madin has noted that the most slide-prone areas are mudstone bedrock and slopes over 25% and areas of rapid sea cliff erosion or riverbank erosion. I would add terrace deposits overlying seaward-dipping mudstone with slopes as flat as 10 degrees. Typically, the landsliding occurs within a few hundred feet of the beachline and during or after heavy or prolonged rainfall. Severe storms that result in pounding and erosion of the sea cliff compound the land movement.

My area of concern is landsliding connected to the subduction, or severe crustal quake. From my observations of the morphology of the marine terrace deposits up and down the Oregon coast, abnormal drainage patterns appear to be common. Erosion of the Coast Range and nearshore sediments should result in drainage ways perpendicular to the coast. Seemingly more often than not, the drainages are deflected at the margins of, or within, the terrace deposits, and for variable distances they parallel the shorelines, as shown on the contour map example used for figure 1.

Figure 2 is the same map as figure 1 with geologic units delineated from the mapping for DOGAMI Bulletin 81 (admittedly very broad and general). Assuming that the terrace deposits are more erodible than the underlying mudstone bedrock units, one would think that the erosional channels would continue straight toward the beach. An argument could be made that the upper (eastward) margin of the terrace deposits has pulled away from the underlying bedrock, creating a new drainage path. One could also imply from figure 2 that the Astoria and Nye mudstone formations could have undergone similar movements.

These terrace deposits were apparently once uniform sand or poorly indurated sandstone that rested on seaward-sloping or dipping mudstones. From my experience, when excavating the terrace deposits one finds that they are highly fractured and contain large volumes of water. Normal coastal erosion and saturation by heavy rainstorms can cause, and has caused, sections to break off and slide onto the beach. The active sliding is usually within one or two hundred yards of the beach. My concern is that this pattern of fracturing (figure 1) continues many hundreds of yards inland. Observations also show that the fractures farther from the shoreline do not appear to show any recent movement.

Figure 3 depicts a possible sequence of events without specific ages or intervals.

This phenomenon could possibly contain a geologic record in the form of Carbon-14 from buried organics or tree rings (if any old enough still exist) in the base of the ravines. Assuming that all of the fractures did not occur simultaneously, different ages may be established for different events. At the very worst, a most recent event may be isolated.

In summary, I feel that the research is moving steadily forward. This is serious business. I urge the researchers to avoid searching for data to fit preconceived notions (one set of errors can mean hundreds of years for recurrence intervals). Coastal governments should not panic; the probability for disaster was the same in the last decade as it will be in the next.

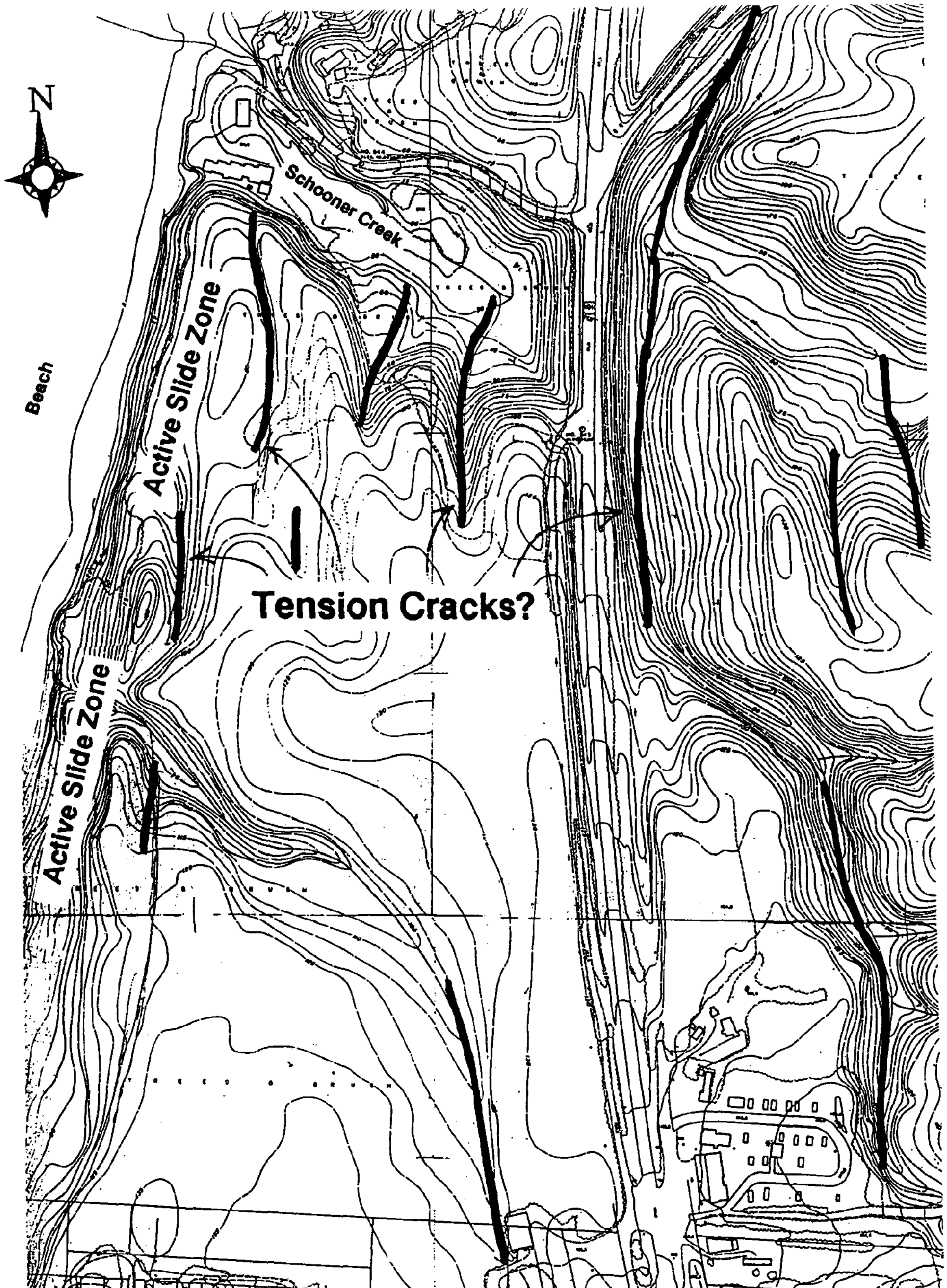

N
Schooner Creek
Beach
Active Slide Zone
Active Slide Zone
Tension Cracks?

Figure 1.

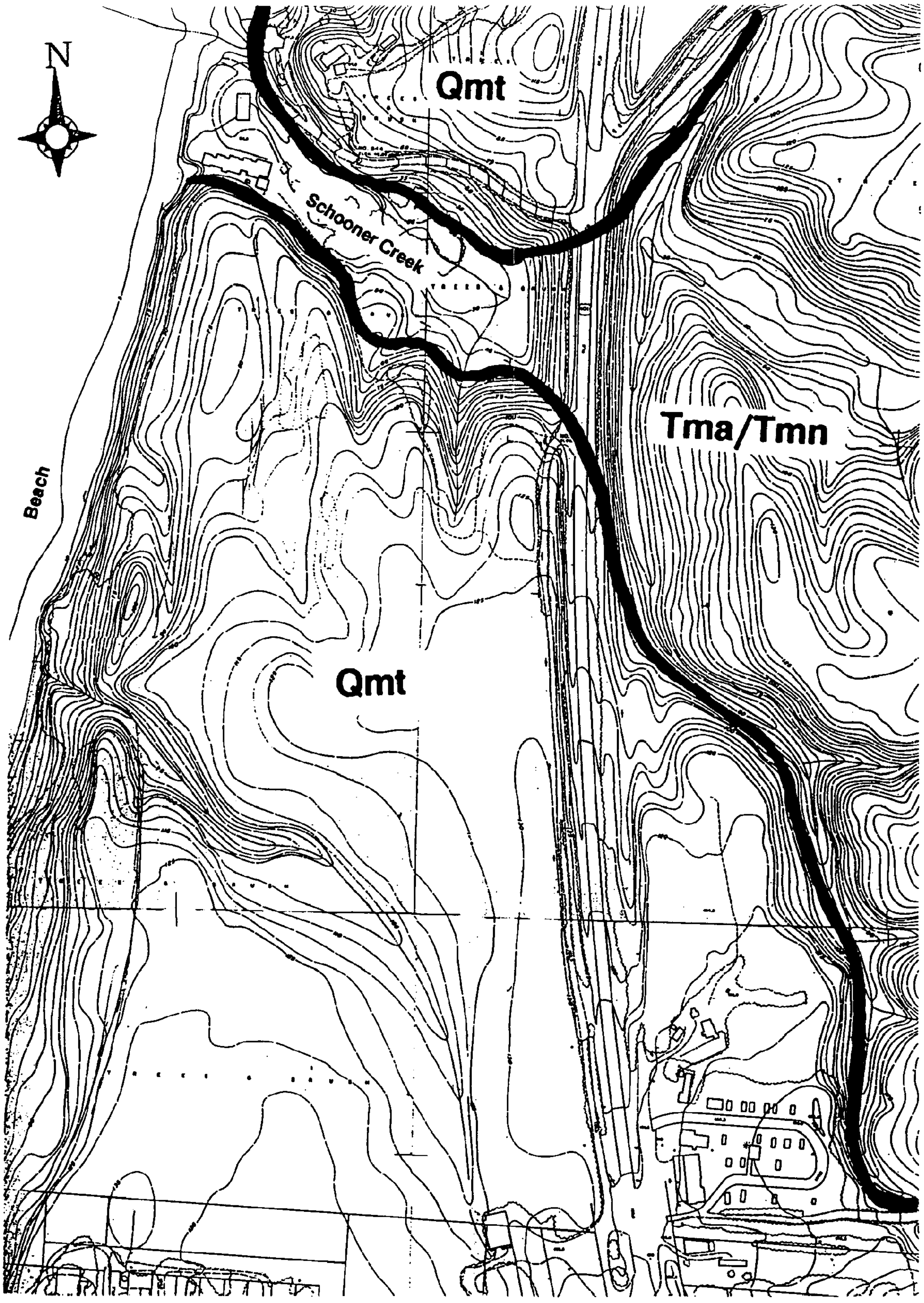


Figure 2.

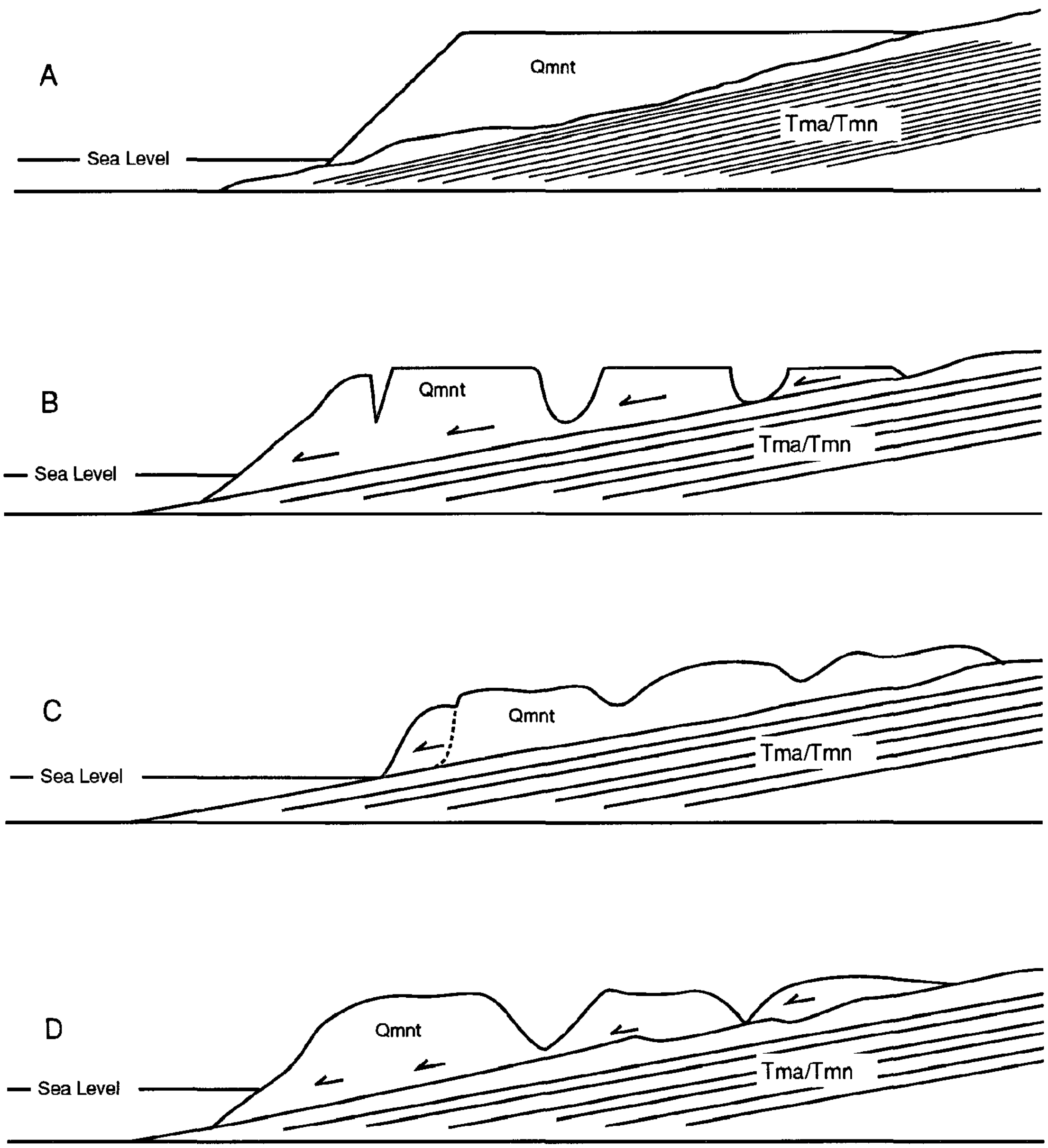


Figure 3.
A. Uplifted terrace deposits in equilibrium. No disturbance.
B. Subduction quake. Terrace deposits move along bedrock surface, creating fractures parallel to the shoreline. Note movement into zone of maximum erosion potential and parallel to the shoreline. Note movement into zone of maximum erosion potential and downwarping.
C. Long period of quiescence (perhaps today?). Note that beach erosion has moved terrace deposits back to sea level/ bedrock contact. Nearshore landsliding is continual as the result of wave undercutting. Ravine slopes reaching natural angle of repose.
D. Subduction quake (tomorrow?). Terrace deposits again move into zone of maximum erosion. Destruction of structures on marine terrace deposits. Ravines open up again.

COMMENTS ON PAPER BY IAN MADIN

Rainmar Bartl
Clatsop-Tillamook Intergovernmental Council

How do we plan for a catastrophic event that has a low probability of occurring at any given time but that, when it does occur, will have enormous consequences? At the conclusion of his paper, Ian Madin suggests a number of steps various parties should initiate in light of our knowledge about earthquakes in subduction zones. I agree with their general direction and offer the following additional comments.

Emergency Planning

The first step in emergency planning is to increase the level of public awareness. Most Californians know about the San Andreas fault. But how many Oregonians are aware of the potential for a devastating earthquake in their state?

We can learn from public information campaigns in California and perhaps those in the south, where officials are used to dealing with hurricanes. This is an area in which the Federal Emergency Management Act (FEMA) should be doing a lot more.

Any public information campaign will be complicated by the large number of tourists and visitors in coastal communities. How can we reach this group effectively?

Buildings

1. Reinforcing Public Buildings

Ideally, public facilities should be retrofitted to withstand earthquakes. I agree with Madin's conclusion that little will occur. With budgets limited, such improvements are likely to be a very low priority. Cannon Beach had some experience with this last year. The city hall is of masonry and would not be safe in an earthquake. For this reason, a consultant had recommended extensive repairs. However, after lengthy discussions of the situation, the city council voted to make only minor repairs.

2. Building Codes/FEMA

There is a conflict between FEMA flood regulations, which require the construction of piling-supported buildings in coastal high-hazard areas, and the poor performance of such structures in an earthquake. Is there some way to reconcile this conflict?

The same conflict exists where pile-supported structures have been built in filled estuaries and flood plains. Much of Cannon Beach's downtown is located in a filled wetland, and I suspect this is not uncommon for other coastal towns located on estuaries.

Land Use Planning

1. Relocation of Threatened Structures

It will be difficult to relocate a public facility that is currently in an area at high risk from tsunamis until that facility is totally worn out. An example of such a structure is the Cannon Beach grade school, which is located on the Ecola Creek estuary, an area extremely susceptible to tsunami hazard.

2. Planning for Tsunami Hazard

Present FEMA mapping and regulations do not consider tsunami hazards, either from a distant earthquake or from one in the subduction zone. Should they? Is it technically feasible to prepare for a tsunami? If so, what might be the implications of incorporating tsunami planning into the regulations, including its effect on insurance rates?

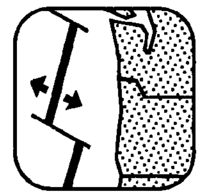
The fact that a tsunami wave could reach 10 meters or more does not leave much room for land use planning in many communities. For example, in Cannon Beach, the elevation of downtown is 12 feet mean sea level (MSL). The area is protected by a dike with a height of 20 to 25 feet MSL. Many of the city's oceanfront areas have a height of less than 30 feet MSL.

CATASTROPHIC COASTAL HAZARDS IN THE CASCADIA MARGIN U.S. PACIFIC NORTHWEST

Curt Peterson
Geology Department, Portland State University

George Priest
Oregon Department of Geology and Mineral Industries

SCIENCE



PACIFIC NORTHWEST COASTAL EARTHQUAKE, TSUNAMI, AND LANDSLIDE HAZARDS

After decades of debate, scientists now believe that the Cascadia subduction zone, encompassing the Pacific Northwest (PNW) coastal zone , is coseismic, that is, predisposed to earthquakes. Prehistoric earthquakes of potentially very large magnitude (+8.5 Mw) are implied by past episodes of abrupt coastal subsidence, tsunami inundation, and sediment liquefaction (table 1; Atwater 1987; Reinhart and Bourgeois 1989; Darienzo and Peterson 1990; Vick 1988; Peterson et al. 1991a; Carver, pers. comm.). The prehistoric subduction zone earthquakes are estimated to have taken place at intervals of between 300 and 600 years, with the last event occurring about 300 years ago.

While earthquake sources, magnitudes, and recurrence intervals in the Cascadia margin are currently being investigated (Shedlock and Weaver 1991) little is being done to establish site-specific risks from the collateral earthquake effects. Locally, these effects can include unconsolidated sediment liquefaction, coastal landslides, tsunami inundation, and persistent shoreline subsidence and related flooding. The magnitude of coastal subsidence (zero to two meters relative sea level rise) could vary regionally, producing extensive beach erosion and severe seasonal flooding in bays and tidal-river flood plains. Beach retreat might shift some shorelines landward by as much as 100 meters. We estimate that as much as 90 percent of the present wetlands and low pastures in some bays will be submerged following the next subsidence event. For the most part, PNW coastal planners at present have little or no site-specific data with which to address concerns about these collateral seismic hazards.

In addition to earthquake hazards, the catastrophic responses of some PNW beaches to the anomalous storm conditions of the 1982-83 El Niño event (Komar 1986; Tuttle 1987) have clearly shown the susceptibility of the beaches to extreme interannual climatic events. Sustained beach erosion, sand dune accretion, or coastal flooding were experienced in many PNW coastal zone beaches following the longshore redistribution of beach sands during the 1982-83 winter period. Some beaches experienced northward sand displacements of 5 to 10 million cubic meters, over multikilometer distances, for a duration of several years (Peterson et al. 1990). The northward shift in beach sand resulted from an unusually oblique approach of winter storm waves associated with anomalously low latitudes of North Pacific storm centers in 1982-83. The delayed return of beach sand to the south (1986 and 1987) followed a two-year period of high-latitude winter storms (1984 and 1985) that were unable to mobilize the northward displaced sand (Peterson et al. 1992). The several years following the 1982-83 El Niño appear to be the most widespread erosional period in the PNW coastal zone during the last several decades.

Locally, the multiyear redistribution of littoral sand (1) stripped beaches to underlying bedrock, (2) exposed sea cliffs and foredunes to direct wave attack, or (3) caused the rapid growth of eolian dune fields (dunes caused by wind). The presence of jetties, for example those at Humboldt Bay and at the mouths of the Siuslaw, Yaquina, and Columbia rivers, might have contributed to the post-El Niño effects of local beach erosion. Furthermore, the long-term effects of sea walls, dune stabilization, and offshore dredge

Locality	Abrupt Subsidence	Tsunami	Liquefaction
Neah Bay, WA	X*		
Kalaloch, WA	X		X
Copalis, WA	X*	X*	X*
Grays Harbor, WA	X*	X*	
Willapa Bay, WA	X*	X*	X
Seaside, OR	X	X	
Cannon Beach, OR	X	?	
Nehalem, OR	X**	X**	
Tillamook Bay, OR	X	?	
Netarts, OR	X	X	X
Pacific City, OR	X	X	X
Neskowin, OR	X		
Lincoln, City, OR	X**	X**	X
Gleneden Beach, OR			X
Newport, OR	X	X	X
Waldport, OR	X	X	?
Florence, OR	?	?	
Reedsport, OR	X	?	
Coos Bay, OR	X***		X
Bandon, OR	X	?	X
Langlois, OR			X
Port Orford, OR			X
Gold Beach, OR			X
Arcata, CA	X****		X****
Eureka, CA	X****		X****

Published and unpublished data from PSU Geology Department and other sources listed below:
*Pers. Comm., B. Atwater, USGS and J. Bourgeois, UW
**Pers. Comm., W. Grant, USGS
***Pers. Comm., A. Nelson, USGS
****Pers. Comm., G. Carver, HSU
? Features tentatively identified.

Table 1. Sites showing possible evidence of Cascadia margin Paleoseismicity in Late Holocene and Late Pleistocene coastal deposits. Data compiled in September 1991.

disposal on littoral sand supply in the PNW coastal zone have not been quantitatively evaluated. Of particular concern are the additive impacts of (1) extreme changes in storm wave climate, (2) physical restrictions to longshore transport, and (3) diminished sand supply on existing beach sand buffers. Because coastal managers have not had much experience with such unusual erosional events, they generally have not considered the potential impacts of interannual redistributions of beach sands during shoreline planning or permitting processes.

In addressing these newly identified coastal hazards, it is important to recognize the diversity of shoreline conditions and associated hazard susceptibilities in the PNW coastal zone. For example, the open ocean shoreline from the Juan de Fuca Straits, Washington, to Cape Mendocino, California (1,000 kilometers in distance), contains some 42 separate beach segments. These segments possibly represent proxies for independent littoral cells (2 to 165 kilometers long) totaling some 770 kilometers, or about 77 percent of the coast (Peterson et al. 1991b). Catastrophic shoreline erosion could differ between and within these beach segments as a function of the local distribution of beach sand buffers. For example, measured sand volumes in selected beaches range from 15 to 3,400 cubic meters per meter of shoreline (Peterson et al. 1991c). As yet, no quantitative relations between pre-existing sand volume and susceptibility to catastrophic erosion have been established in the PNW coastal zone.

Some 38 of the beach segment boundaries, that is, about 45 percent of the cell-bounding headlands, project less than 500 meters seaward of adjacent shoreline embayments. Assuming 0.01 to 0.02 nearshore gradients (slope), these small headlands can be expected to terminate in less than 10 meters of water, well within reported water depths of active sand suspension and transport (U.S. Army Corps of Engineers 1973). However, no field experiments have been conducted to test the effects of these small headlands in restricting longshore transport under highly variable conditions of directional wave climate. For example, chronic beach erosion or dune sand accretion in some cells might result from infrequent events of sand bypassing around small headlands during extreme climatic events. Finally, there have been no studies of the potential long-term flux of beach sand between inshore, offshore, or longshore sand reservoirs following sustained coastal subsidence (decades) associated with earthquake subsidence or uplift.

An increasing concern of many PNW coastal communities is their susceptibility to near-source tsunami hazards. In the event of a megathrust earthquake in the central Cascadia margin, as few as 20 minutes might elapse between the termination of seismic shaking and the advance of the corresponding tsunami (Baptista, pers. comm.). Although evidence of prehistoric tsunami inundation is now established in more than a dozen PNW bays (table 1), the geologic records do not provide accurate estimates of the heights of tsunami run-ups. Preliminary computer numeric models of tsunami generation and shoreward propagation have been developed for the Cascadia margin (Hebenstreit 1988; Baptista, pers. comm.). However, a great deal of work is needed to refine the models for accurate prediction of tsunami onshore run-up (land elevations swept by the tsunami wave) and inshore attenuation (landward distance reached by the tsunami). In addition to the uncertainty of tsunami run-up, the lack of detailed coastal topography (land elevations) severely limits the prediction of site-specific tsunami hazard needed by planners and emergency managers.

Of the beach-fronted PNW coastline, approximately 460 kilometers (60 percent of the total) are backed by unconsolidated dune or bay deposits. The remainder (40 percent of the total) are backed directly by sea cliffs. Unconsolidated beach, dune, and bay sediments within reach of perched water tables are likely to be the foundation soils most susceptible to liquefaction from seismic shaking. Ironically, the flat topography and close proximity of these deposits to modern shorelines make them very appealing to private and commercial developers. Although liquefiable deposits have been mapped in the Portland and Seattle metropolitan areas, they have not been regionally mapped or systematically tested for liquefaction potential anywhere in the PNW coastal zone.

Seasonal and interannual variations in eolian dune sand supply are major complicating factors in coastal planning for shoreline development, jetty maintenance, harbor mouth dredging, and dune habitat ecology. Surprisingly little information exists regarding the site-specific rates of beach sand transport by eolian processes in the PNW coastal zone. It has been suggested that sand supplies to dune fields are alternately terminated and reactivated following periods of coseismic cycles of subsidence and uplift, respectively (Hunter, pers. comm; Carver, pers. comm.). Unfortunately, there have been few geologic studies of the origin of the major dune fields, their timing of formation, or their long-term growth dynamics since Cooper's pioneering work (Cooper 1958 and 1967). Finally, there have been no quantitative, site-specific studies on the long-term effects of the "locking up" of beach sand in artificially stabilized dune fields, for example, foredunes stabilized by dune grass plantings or shore protection structures.

Most of the beach-fronted sea cliffs contain poorly consolidated Pleistocene deposits overlying wave-cut marine terraces, tectonically upwarped between 0 and 120 meters above present sea level. The longshore distribution of modern sea cliff failures appears to vary widely in northern Oregon (Galster 1987; Komar and Shih 1991) as well as throughout the PNW. Although some 90 percent of the observed sea cliffs in the PNW coastal zone are oversteepened, less than 10 percent of modern sea cliff shoreline (pre-1982-83 El Niño) shows evidence of catastrophic slope failure (Peterson et al. 1992). In addition, we find no regional correlations between reported modern uplift rates (Mitchell et al. 1991) and apparent sea cliff retreat in the Cascadia margin. We speculate that periods of rapid sea cliff retreat immediately follow coseismic subsidence events or anomalous conditions of beach sand redistribution. The susceptibilities of existing sea cliffs to future erosion and retreat, due either to coseismic tectonic subsidence (abrupt sea-level rise) or interannual events of sand redistribution by anomalous wave climate, have yet to be evaluated in the Cascadia margin.

In conclusion, the PNW coastal zone is particularly susceptible to Cascadia margin earthquakes from the multiple threats of (1) relative proximity to earthquake epicenters, (2) near source tsunami run-up, (3) abundance of liquefiable foundation soils, and (4) persistent coastal subsidence and flooding. The less dramatic, but potentially more frequent, events of unusual wave climate make "apparently stable" shorelines in the PNW coastal zone far more dynamic then previously assumed. Finally, increasing development pressures on shoreline properties are certain to yield increasing land-use conflicts between people who want to build artificial structures and the natural dynamics of shoreline erosion or accretion. Coastal planners, emergency managers, and the general public need comprehensive assessments of potential, catastrophic shoreline hazards resulting from earthquakes and extreme climatic conditions in the Cascadia margin. Focused research efforts are now needed to provide site-specific information for catastrophic hazard mitigation in the Pacific Northwest coastal zone.

Acknowledgments

Work on natural coastal hazards performed by the Geology Department at Portland State University has been recently supported by the National Coastal Research Institute grants no. 2-5632-03 and CZ17.90-5635-01, the USGS National Earthquake Preparedness Program grants 14-08-0001-G1512 and 14-08-0001-G2120, the Oregon Department of Geology and Mineral Industries interagency agreements 1989-1991, and the National Science Foundation grant EAR-8903903.

References

Atwater, B.F., 1987. Evidence for great Holocene earthquakes along the outer coast of Washington State: Science 236:942-944.

Cooper, W.S., 1958. Coastal sand dunes of Oregon and Washington: Geological Society of America Memoir 72, 169 p.

Cooper, W.S., 1967. Coastal dunes of California: Geological Society of America Memoir 104, 131 p.

Darienzo, M.E., and C.D. Peterson, 1990. Episodic tectonic subsidence of late-Holocene salt marsh sequences in Netarts Bay, Oregon, Central Cascadia Margin, USA. Tectonics 9:1-22.

Galster, R.W., 1987. A survey of coastal engineering geology in the Pacific Northwest: Bulletin of the Association of Engineering Geologists 24:161-197.

Hebenstreit, G.T., 1988. Local tsunami hazard assessment for the Juan de Fuca plate area. Unpublished Report for US Geological Survey, National Earthquake Hazard Reduction Program.

Komar, P.D., 1986. The 1982-83 El Niño and erosion on the coast of Oregon: Shore and Beach 54:3-12.

Komar, P.D., and S.M. Shih, 1991. Sea-cliff erosion along the Oregon coast. ASCE, Coastal Sediments 91 Proceedings, pp.1558-1570.

Mitchell, C.E., R.J. Weldon, P. Vincent, and H.L. Pittock, 1991. Active uplift of the Pacific Northwest Margin: EOS Transactions, American Geophysical Union 72:314.

Peterson, C.D., P.L. Jackson, D.J. O'Neil, C.L. Rosenfeld, and A.J. Kimerling, 1990. Littoral cell response to interannual climatic forcing 1983-1987 on the central Oregon coast, USA: Journal of Coastal Research 6:87-110.

Peterson, C.D., M. Hansen, and D. Jones, 1991a. Widespread evidence of paleoliquefaction in late-Pleistocene marine terraces from the Oregon and Washington margins of the Cascadia subduction zone. EOS, Trans. Amer. Geophys. Union 72:313.

Peterson, C.D., M.E. Darienzo, D.J. Pettit, P. Jackson, and C. Rosenfeld, 1991b. Littoral cell development in the convergent Cascadia margin of the Pacific Northwest, USA. In. R. Osborne (ed) From Shoreline to the Abyss, Contributions in Marine Geology in Honor of F.P. Shepard, SEPM Special Publication 46:17-34.

Peterson, C.D., D.J. Pettit, M.E. Darienzo, P.L. Jackson, C.L. Rosenfeld, and A.J. Kimerling, 1991c. Regional beach sand volumes of the Pacific Northwest, USA. Coastal Sediments 91 Proceedings Speciality Conference, pp. 1503-1517.

Peterson, C.D., M. Hansen, G. Briggs, R. Yeager, I. Saul, P.L. Jackson, C.L. Rosenfeld, and T.A. Terich, 1992. Regional sediment dynamics and shoreline instability in littoral cells of the Pacific Northwest. Final Project Report to National Coastal Resources Research and Development Institute, Newport, Oregon, 45 p.

Pettit, D. J., 1990. Distribution of sand within selected littoral cells of the Pacific Northwest. Unpublished Masters Thesis, Portland State University, Portland, Oregon, p. 249.

Reinhart, M.A., and J. Bourgeois, 1989. Tsunami favored over storm or seiche for sand deposit overlying buried Holocene peat, Willapa Bay, WA (abstract). EOS 70:1331

Shedlock, K.M., and C.S. Weaver, 1991. Program for Earthquake Hazards Assessment in the Pacific Northwest. USGS Circular 1067.

Tuttle, D.C., 1987. A small communities response to catastrophic coastal bluff erosion. ASCE Fifth Symposium on Coastal and Ocean Management, Coastal Zone '87 2:1876-1881.

U.S. Army Corps of Engineers, 1973. U.S. Army Corps of Engineers Research Center, Shore Protection Manual, U.S. Government Printing Office, Washington D.C.

Vick, G.S., 1988. Late Holocene paleoseismicity and relative sea level changes of the Mad River Slough, northern Humboldt Bay, California. Masters Thesis, Humboldt State University, Arcata California.

SCIENCE

COASTAL PROCESSES AND HAZARDS

OCEAN PROCESSES AND HAZARDS ALONG THE OREGON COAST

Paul D. Komar
College of Oceanography, Oregon State University, Corvallis, Oregon

Introduction

Visitors to the Oregon coast are impressed by the tremendous variety of its scenery. The low rolling mountains of the Coast Range serve as a backdrop for most of the length of its ocean shore. In the south the Klamath Mountains extend to the coast, and the edge of the land is characterized by high cliffs being slowly cut away by ocean waves. The most resistant rocks persist as sea stacks scattered in the offshore. Sand and gravel are able to accumulate only in sheltered areas, where they form small pocket beaches within the otherwise rocky landscape.

The more extensive stretches of beach are found in the lower-lying parts of the coast. The longest continuous beach extends from Coos Bay northward to Heceta Head near Florence, a total shoreline length of some 60 miles. This beach is backed by the impressive Oregon Dunes, the largest complex of coastal dunes in the United States. Along the northern half of the coast there is an interplay between sandy beaches and rocky shores. Massive headlands jut out into deep water, their black volcanic rocks resisting the onslaught of even the largest storm waves. Between these headlands are stretches of sandy shoreline

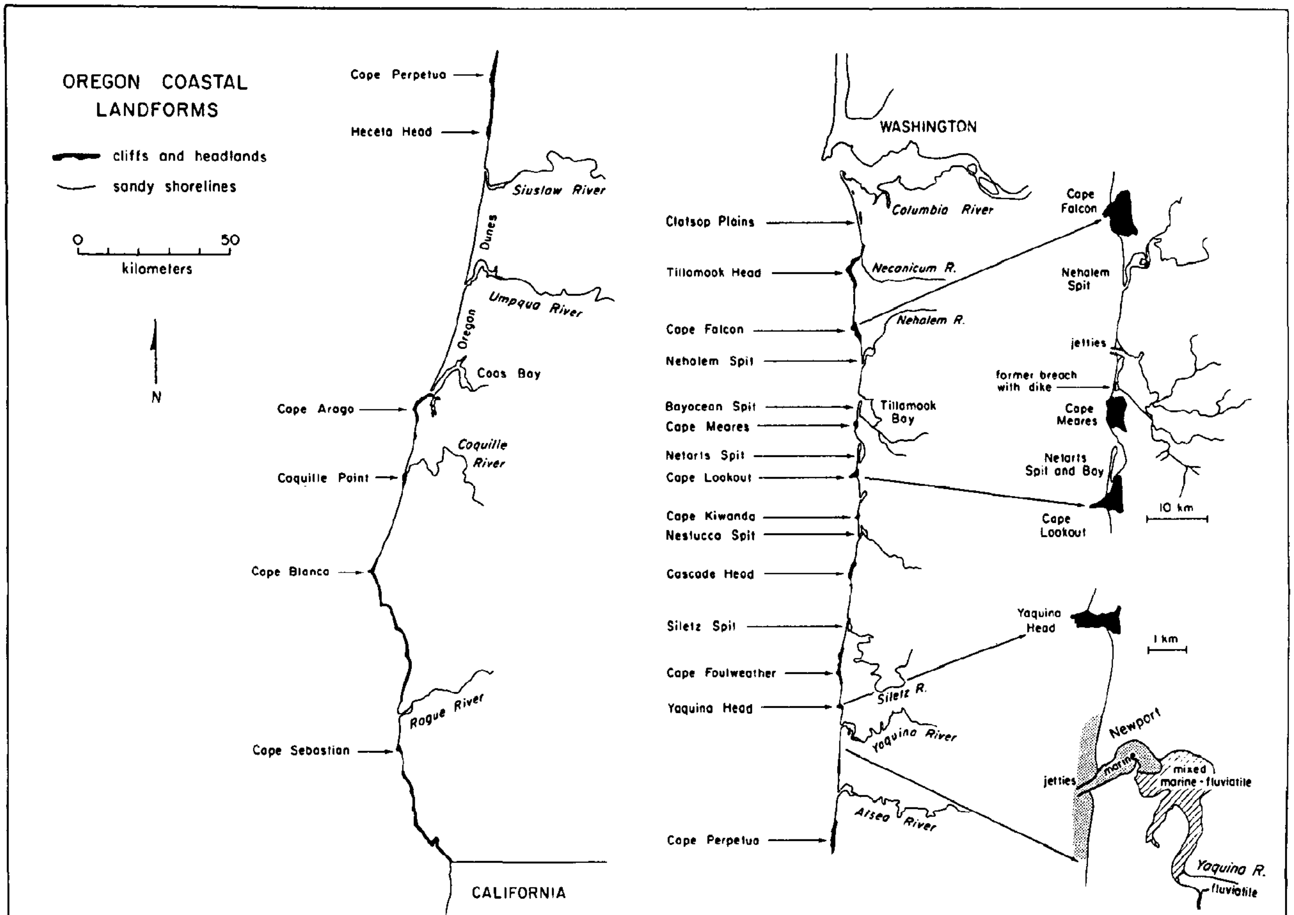


Figure 1: Coastal landforms of Oregon, consisting of stretches of rocky shorelines and headlands, separating pockets of sandy beaches. (From Komar [1985])

whose lengths are governed by the spacings between the headlands (figure 1). Portions of these beaches form the ocean shores of sand spits such as Siletz, Netarts, Nehalem, and Bayocean. Landward from the spits are bays or estuaries of rivers that drain the Coast Range.

The first western explorers and settlers were attracted to the Oregon coast by the potential richness of its natural resources. Earliest were the traders, who obtained pelts of ocean otter and beaver from the Indians. Later came prospectors, who sought gold in the beach sands and coastal mountains, but who in many cases were content to settle down and "mine" the fertile farm lands found along the river margins. Others turned to fishing, supporting themselves by harvesting the abundant Dungeness crab, salmon, and other fish in the coastal waters. Also important to the early economy of the coast were the vast tracts of cedar and sitka spruce. Their significance continues to the present. However, today the most important "commodity" for the Northwest coastal economy is the vacation visitor: vacationers arrive by the thousands during the summer months.

It is still possible, in spite of the number of tourists who visit the state, to leave Highway 101 and find the seclusion of a lonely beach or the stillness of a trail through the forest. However, there is cause for concern that the qualities of the Oregon coast we cherish are being lost. Like most coastal areas, Oregon is experiencing developmental pressures. Homes and condominiums are being constructed immediately behind the beaches, within the dunes, and atop cliffs overlooking the ocean. Everyone wants a view of the waves, passing whales, and the evening sunset, as well as easy access to a beach, but these desires are not always compatible with nature. As a result, increasingly homes are being threatened and sometimes lost to beach erosion and cliff landslides. Such problems can usually be avoided if builders recognize that the coastal zone is fundamentally different from inland areas because of its instability. Builders need some knowledge of ocean waves and currents and how they shape beaches and attack coastal properties. In addition, they need to understand and recognize potential instabilities of the land that might cause it to suddenly slide away. A familiarity with the processes and types of problems experienced in the past can aid in the selection of a safe location for a home. It can also enhance people's enjoyment of the coast, and, it is hoped, lead to an appreciation of the qualities of the Oregon coast that must be preserved.

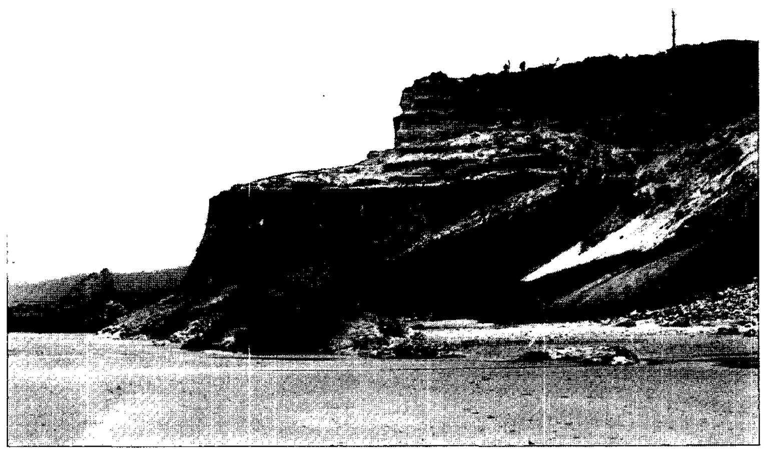
Tectonic Setting and Geomorphology

The tectonic setting of the Oregon coast is extremely important to the occurrence and patterns of erosion. Significant is the presence of active sea-floor spreading beneath the ocean to the immediate west. New ocean crust forms at the Juan de Fuca and Gorda ridges, adding to the Juan de Fuca and Gorda South plates. These oceanic plates, which are moving generally eastward toward the continent, collide with the North American plate, which includes the continental land mass. The collision zone lies along the margin of the coasts of Washington, Oregon, and northern California. There is evidence that the oceanic plates have been undergoing subduction beneath the continental North American plate, evidence which includes the still-active volcanoes of the Cascades, the existence of marine sedimentary rocks accreted to the continent, and the occurrence of vertical land movements along the coast.

Most of the marine sediments deposited on the oceanic plates are scraped off during the subduction process and accrete to the continental plate. The addition of ocean sediments to the continent has led to the long-term westward growth of the Pacific Northwest. The oldest rocks found in the Coast Range date back to the Paleocene and Eocene periods, some 40 to 60 million years ago. These accreted marine sediments, mainly gray mudstones and siltstones, can be seen in many sea cliffs along the coast (figure 2). As will be discussed in a later section, the presence of these mudstones is important to the erosion of sea cliffs and particularly to the occurrence of landslides.

In addition to the Tertiary mudstones, many sea cliffs contain an upper layer of clean sand (figure 2). These are Pleistocene marine terrace deposits and consist of uplifted beach and dune sands. In some areas the Pleistocene sands form the entire sea cliff, with no outcrop of Tertiary mudstones beneath. The flat marine terrace seen

Figure 2: *The sea cliff at Jump-Off Joe, Newport, consisting of seaward-dipping Tertiary mudstones and uplifted Pleistocene marine terrace sands.*



in figure 2 is the lowermost and youngest terrace of a series that in some places form a stairway up the flank of the Coast Range. The presence of this stairway documents that the Oregon coast has been tectonically rising for hundreds of thousands of years, while at the same time the sea level has oscillated because of the growth and retreat of glaciers.

The general uplift of the Northwest coast is also demonstrated by records from tide gauges where the hourly measurements are averaged for the entire year, removing the tidal fluctuations and leaving the mean sea level for that year (Hicks et al. 1983). Examples of up to 80 years in length obtained by yearly averaging are shown in figure 3. Each record reveals considerable fluctuations in the level of the sea from year to year, with many small ups and downs. The sea level in any given year is affected by many oceanic and atmospheric processes. These processes cause the irregular fluctuations.

In spite of such irregularities, most tide-gauge records reveal a long-term rise in the sea that can be attributed in part to the melting of glaciers. The record from New York City in figure 3 is typical of such analyses. In that example the long-term average rise is 3.0 millimeters a year, about 12 inches a century (1 inch = 25 millimeters). The record from Galveston, Texas, also shows a rise, but the average rate is much higher at 6.0 millimeters a year (24 inches a century). The actual level of the sea cannot be going up faster at Galveston than at New York City—the discrepancy results from changing levels of the land which affect the record obtained at a specific tide-gauge site. It is known that the Galveston area is subsiding, so the 6.0 millimeters-a-year record from that tide gauge represents the

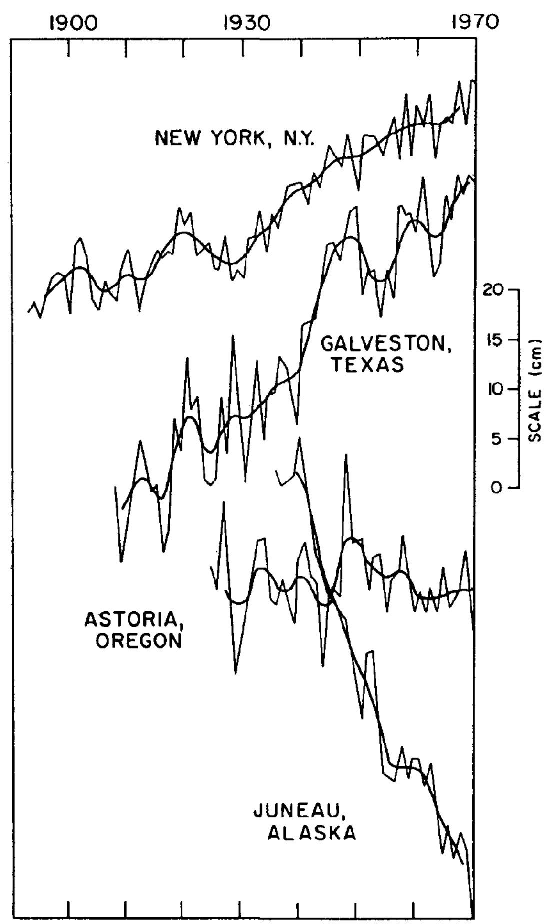


Figure 3: Yearly changes in sea level determined from tide gauges at various coastal stations. (After Hicks [1972])

combined effects of the local land subsidence and the actual rise in sea level. An extreme case of this is Juneau, Alaska, figure 3, which is tectonically rising at a rate that is faster than the rise in sea level. Its tide-gauge record, therefore, indicates a net fall in the water level relative to the land.

The record from the tide gauge at Astoria, Oregon, is included in figure 3—the level of the sea there has remained relatively constant with respect to the land. This must indicate that during at least the last half century, Astoria has been rising at just about the same rate as the sea. A detailed analysis of the measurements from the Astoria gauge indicates that the land is actually rising slightly faster than the water, the net increase in the land relative to the sea being 0.1 to 0.2 millimeters a year. This change is small, amounting to a 10- to 20-millimeter (less than an inch) increase in land elevation if it continued for 100 years. The land must be rising at a faster rate at Neah Bay on the north coast of Washington, where the net rate is 1.3 millimeters a year (5 inches a century) in excess of the global sea-level rise, and at Crescent City in northern California, with 0.7 millimeter a year, or 2.8 inches a century, of net land emergence (Hicks et al. 1983).

Data from geodetic surveys collected by the National Geodetic Survey permit us to infer the movement of the land relative to the sea along the remainder of the Oregon coast. Vincent (1989) and Mitchell et al. (1991) have analyzed the geodetic data along a north-south line extending the full length of the Oregon coast. To establish elevation changes, they compared surveys made in 1931 and 1988; the values are graphed in figure 4. The movement so determined is relative rather than absolute, so the elevation changes have been normalized to the bench mark in Crescent City. Accordingly, the elevation change scale on the left of the diagram gives 0 for Crescent City, while positive values for other locations represent an increase in elevation relative to Crescent City and negative values indicate reduced elevation relative to Crescent City. (However, the elevation could still involve tectonic uplift.) The overall pattern seen in figure 4 indicates that the smallest uplift has occurred along the north-central coast between Newport and Tillamook, with progressively higher uplift further south and along the very northernmost portion of the coast toward Astoria and the Columbia River. The first scale on the right of figure 4 indicates the equivalent rates, calculated as the elevation changes divided by the lapsed time between the surveys (1988-1931 = 57 years). The differential rates are significant; for example, they amount to 2 to 3 millimeters a year when we compare Astoria and the south coast with the Newport and Lincoln City areas. It is possible to use the tide-gauge data to convert the elevation changes relative to Crescent City determined by Vincent (1989) into rates relative to the annual change in the global level of the sea. This is done simply by shifting the first scale on the right of figure 4, that relative to the Crescent City bench mark, by an amount 0.7 millimeter a year determined from the tide gauge at that location. This shift yields the rate scale farthest to the right in figure 4, the rate of land-level change relative to the changing global sea level. A positive value again indicates that the elevation of the land is increasing relative to the sea, while a negative value corresponds to inundation of the land by the rising sea. This coast-wide shift of the

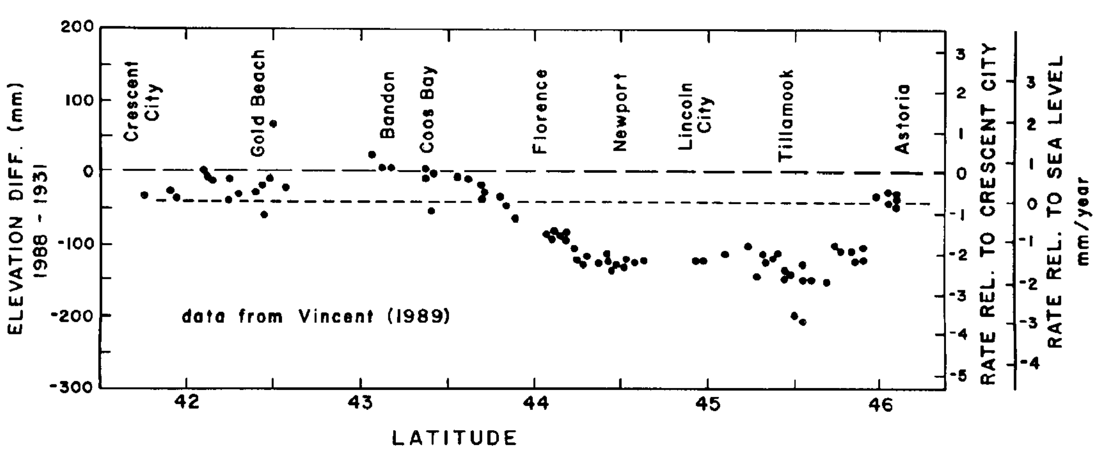


Figure 4: Elevation changes and their relationship to sea-level rise along the length of the Oregon coast from Crescent City in California north to Astoria on the Columbia River, based on repeated geodetic surveys along the coast. (After Vincent [1989])

scale by 0.7 millimeters a year, based on the tide gauge at Crescent City, indicates that Astoria at the far north is rising faster than the sea by an amount on the order of 0.1 to 0.2 millimeter a year, the same measurement recorded by the tide gauge at that location. These matching data confirm (1) the validity of the geodetic data analyzed by Vincent to determine elevation changes and (2) the analyses undertaken to convert that data into a rate of change that can be compared with the increasing level of the sea.

According to the results graphed in figure 4, the southern half of the Oregon coast is currently rising faster than the global sea level, as is the far north coast near Astoria. Conversely, the central stretch between Newport and Tillamook is being submerged by the rising sea. The latter rates are on the order of 1 to 2 millimeters a year (4 to 8 inches a century), and therefore are small compared with submergence rates experienced on most coastlines: rates of 4 to 6 millimeters a year (16 to 24 inches a century) are common along the east and Gulf coasts of the United States (figure 3). The global rise in sea level has been estimated by various workers to be on the order of 1 to 3 millimeters a year (4 to 12 inches a century), the large range being due to the difficulty of separating that worldwide component from local tectonic and isostatic effects included in records from tide gauges. Assuming that the eustatic rise in sea level is on the order of 2 millimeters a year (8 inches a century), the results from figure 4 indicate that the south coast of Oregon is tectonically rising at about 2 to 3 millimeters a year (8 to 12 inches a century) whereas the stretch between Newport and Tillamook is approximately stable, neither rising nor falling tectonically.

It is apparent that the along-coast differences between tectonic uplift and changing levels of the sea deduced from figure 4 will be relevant to spatial patterns of coastal erosion. However, there also appears to be a temporal change in the tectonics that is important to erosion. Earthquake activity is generally associated with a subduction zone such as that in the Northwest, where seismic events are triggered by the plates scraping together as the oceanic plate slides beneath the continental plate. The Northwest coast is anomalous in that respect in that there have been no historic earthquakes which can be attributed to plate subduction. However, recent evidence suggests that the plates are temporarily locked together and that the 200-year historical record from the Northwest is too short to establish whether earthquakes do accompany subduction. This evidence has come from investigations of estuarine marsh sediments buried by sand layers, deposits which suggest that during prehistoric times portions of the coast have abruptly subsided, generating an extreme tsunami that swept over the area to deposit the sand (Atwater 1987; Atwater and Yamaguchi 1991; Darienzo and Peterson 1990). Based on the number of such layers found in Willapa Bay, Washington, and Netarts Bay, Oregon, it has been estimated that catastrophic earthquakes have occurred at least six times in the past 4,000 years, at intervals ranging from 300 to 1,000 years. The last recorded event took place about 300 years ago. Therefore, there is strong evidence that major subduction earthquakes do occur along the Northwest coast, but with long periods of inactivity between events.

An earthquake releases strain built up by subduction. This results in some areas of the coast dropping by 1 to 2 meters (3 to 6 feet) during the release, while other areas undergo minimal subsidence. Between earthquake events the strain accumulates; this produces a general uplift of the coast as recorded by the tide gauges and geodetic surveys within historic times (figures 3 and 4).

Another potential change in the present-day pattern of sea-level rise versus coastal uplift is associated with predictions that future greenhouse warming will accelerate the rise in sea level. Some scientists have predicted that global temperatures will increase from 1.5° to 4.5° by the year 2050 (National Research Council 1983). These predictions in turn have led to a variety of estimates for accelerated sea-level rise caused by increased glacial melting and thermal expansion of seawater. For example, a report by the National Research Council (1987) predicts that by the year 2025, the global sea level will have risen 10 to 21 centimeters (4 to 8 inches). Although this may seem insignificant, the effects on sandy shorelines may be magnified 100 times in the horizontal direction, resulting in shoreline erosion of 10 to 21 meters (33 to 70 feet). There are many uncertainties in these analyses of sea-level rise caused by greenhouse warming, and the resulting predictions have been controversial among scientists. Different investigators studying sea-level curves derived from tide gauges have reached conflicting results, some concluding that they see an increase in the rate of rise in recent decades and others concluding that they do not. Despite the uncertainties, there is a growing consensus that some increased rate of sea-level rise can be expected in the next century. This recognition has led to recommendations that future sea levels be given more serious consideration in coastal management decisions.

Ocean Processes as Agents of Erosion

The Northwest coast is one of the most dynamic environments in the world. Ocean waves and currents continuously reshape the shoreline. Portions of the beach are cut away while others are built out. Severe storms strike the coast during the winter, generating strong winds that drive rain against sea cliffs and homes and form huge ocean waves that crash against the shore. Beaches, giving way to waves and currents, retreat toward the land. At times this beach loss continues until the erosion threatens structures and cuts away at public parklands.

Ocean Waves

The extreme seasonality of the Oregon climate results in parallel variations in ocean processes that exert the primary control on natural cycles observed on beaches. The energy of ocean waves parallels the seasonality of storm winds because the strength of those winds is the primary factor in causing the growth of waves. In general, the greater the wind velocity blowing over the surface of the ocean, the higher the resulting waves. Other factors are involved in addition to the wind speed. One is the duration of the storm—the longer the winds blow, the more energy they are able to transfer to the waves. The third factor is the fetch, the area or ocean expanse over which the storm winds are effective. Fetch operates much like storm duration in that the area of the storm governs the length of time the winds are able to act directly on the waves. As the waves are forming they move across the ocean surface and may eventually pass beyond the area of the storm so they no longer acquire energy from the winds. The importance of fetch is apparent when one contrasts wave generation on the ocean with that on an inland lake. The fetch on the lake can be no greater than its length, so the waves can acquire only a small amount of energy from winds before they cross the entire lake and break on the shore.

Wind-generated waves are important as energy-transfer agents. They obtain their energy from the winds, transfer it across the expanse of the ocean, and finally deliver it to the coastal zone when they break on the shoreline. Therefore, the storm need not be in the immediate coastal zone. Waves reach the shores of Oregon from storms all over the Pacific, even from the southern hemisphere near Antarctica. However, the largest waves reaching Oregon derive from winter storm systems that move down from the north Pacific and Gulf of Alaska.

Ocean waves reaching the shores of Oregon are measured daily by a unique system, a microseismometer like those usually employed to measure small earth tremors. In this application the microseismometer senses ground movements produced by ocean waves as they reach the shore and break. Many Coast Guard stations in the Northwest now use this system to obtain better estimates of wave conditions than were formerly determined visually. A microseismometer system is also in operation at OSU Hatfield Marine Science Center in Newport; it is connected to a recorder to obtain a permanent record of the waves. This system has been in operation since November 1971 and has yielded the longest continuous record of wave conditions on the west coast of the United States. These measurements have been valuable in research examining the causes of beach erosion along the Oregon coast.

It might come as a surprise that a microseismometer at the Marine Science Center can provide records of ocean waves—after all, the center is nearly two miles from the ocean. However, even more impressive is that the waves can be detected on the seismometer at Oregon State University in Corvallis, 60 miles inland. When the surf is high on the coast, its effects can be seen as small jiggles in the seismometer recordings.

The microseismometer at the Marine Science Center differs from normal seismometers in that it is tuned to amplify small tremors, whether they are caused by earthquakes too minor to be felt or by ocean waves along the coast. To use the record from the microseismometer to measure ocean waves, it was necessary to first calibrate the system (Creech 1981; Zopf et al. 1976). This was accomplished by obtaining direct measurements of waves in the ocean at the same time their tremors were measured with the microseismometer. The direct measurements of waves were collected with a pressure transducer, an instrument that rests on the ocean bottom and records pressures that are directly proportional to the heights of the waves passing over the transducer. This is the most common method for directly measuring ocean waves, and it would be preferable to use such an instrument rather than a microseismometer. However, winter storms experienced along the Northwest coast are so intense they usually destroy pressure transducers or other wave-measuring instruments that must be placed in the water. On this coast we need a microseismometer that can remain at the Marine Science Center, safe from the reach of waves. Although the direct comparisons between the pressure-transducer records and those obtained with the microseismometer lasted only a few months, the results showed that the motions on the microseismometer are directly proportional to the heights of the offshore waves. Now only the microseismometer is needed to monitor daily ocean-wave conditions.

An example of daily wave measurements obtained from the microseismometer is shown in figure 5, covering the period from mid-December 1972 to mid-January 1973. Most apparent in this series are the storm waves that struck the coast during Christmas. The breaker heights at that time reached 7 meters, about 23 feet, roughly the height of a three-story building. This reported height represents what is termed a "significant wave height," defined as the average of the highest one-third of the waves. The significant wave height can be evaluated from measurements of the waves obtained using wave-sensing instruments. However, it turns out that the significant wave height also roughly corresponds to a visual estimate of a representative wave height. This is because observers normally tend to weight their observations toward the larger waves, ignoring the smallest. There will of course be many individual waves that are still higher than this reported significant wave height, which remains something of an average. Measurements have shown that the largest wave height during any 20-minute interval will be a factor of about 1.8 times

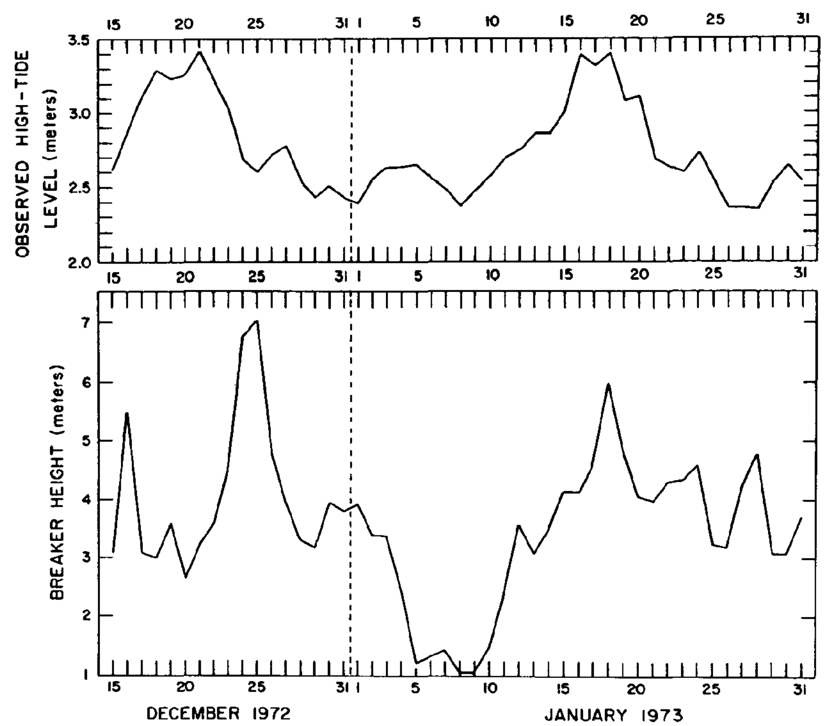


Figure 5: An example of daily variations in wave conditions measured by the microseismometer at Newport, covering the interval from December 1972 through January 1973. (From McKinney [1977])

the significant wave height (Komar 1976). Therefore, when the graph of figure 5 indicates the occurrence of a significant wave height of 23 feet during Christmas 1972, there must have been individual waves of about 1.8 x 23 feet—41 feet high! As might be expected, there was considerable erosion along the coast during that storm, the severest impact having been at Siletz Spit on the mid-Oregon coast.

Figure 6 gives an example of annual changes in wave-breaker heights measured by the microseismometer. The measurements were obtained from July 1972 through June 1973 but are typical of annual variations (Komar et al. 1976a). These data again represent significant wave heights. The solid line gives the average of the significant breaker heights measured during each one-third month interval. It shows that the breakers are on the order of 2 meters high (7 feet) during the summer months and nearly double to about 4 meters (13 feet) in the winter. The dashed lines are the maximum and minimum wave breaker heights that occurred during those one-third month intervals; these extremes provide a better impression of the effects of individual winter storms. The largest waves recorded within this 1972-73 period (the storm waves that are shown on a daily basis in figure 5) reached the coast during the final third of December 1972.

Although extremely high, the waves during that December 1972 storm are well below the largest that have been measured off the Northwest coast. In the early 1960s, a wave-monitoring program on offshore rigs exploring for oil measured an individual wave having a height of 95 feet (Rogers 1966; Watts and Faulkner 1968). This is close to the 112-foot height of the largest wave ever reliably measured in the ocean. It was observed from a naval tanker traveling from Manila to San Diego in 1933 (Komar 1976). All of the measurements on the Oregon coast confirm that it has one of the highest wave-energy climates in the world.

Beach Cycles on the Oregon Coast

Beaches respond directly to the seasonal changes in wave conditions. The resulting cycle (illustrated schematically in figure 7) is similar on most coastlines. The beach is cut back during the winter months of high waves when sand is eroded from the shallow underwater and from the beach berm (the nearly horizontal part of the beach

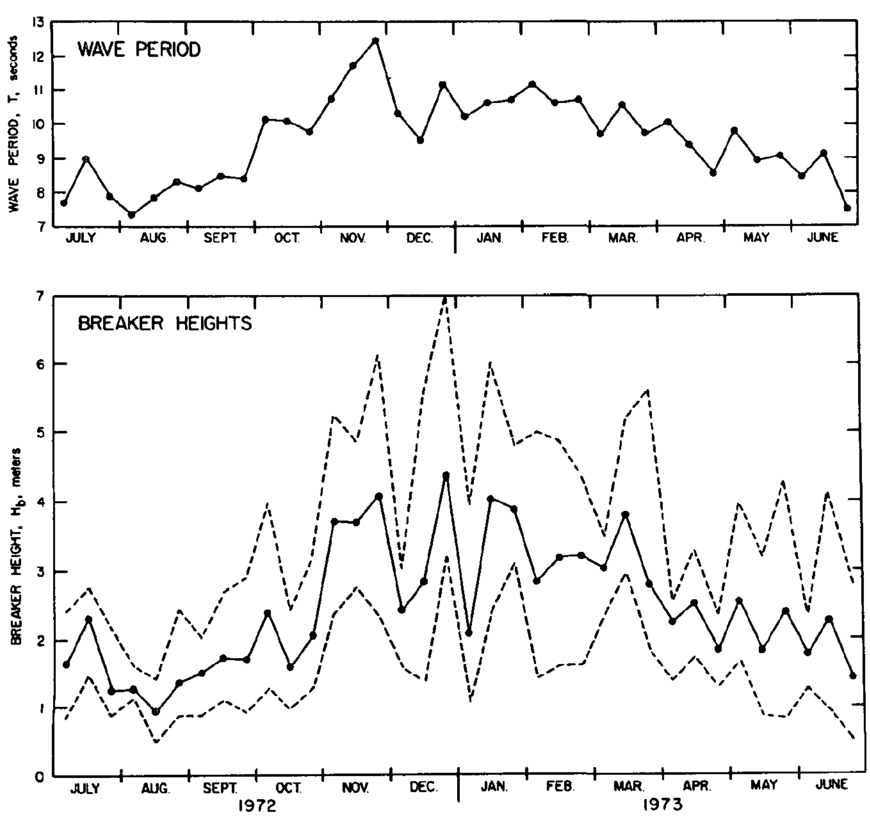
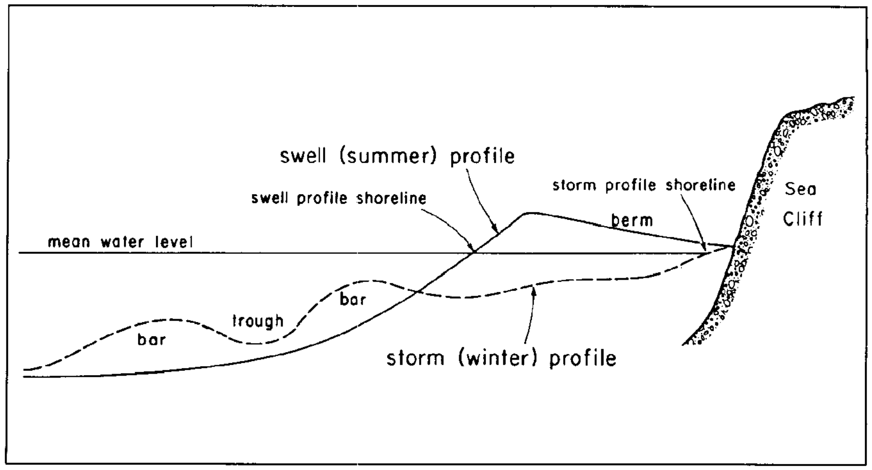


Figure 6: The monthly variations of wave breaker heights and periods at Newport, illustrating the occurrence of higher wave conditions during the winter months. The solid line is for the mean heights (significant wave heights) for one-third month intervals, and the dashed lines are for the largest and smallest breakers for those intervals. (From Komar et al. [1976a])

Figure 7: The general pattern of seasonal changes in beach profiles associated with parallel variations in wave energies. (From Komar [1976])

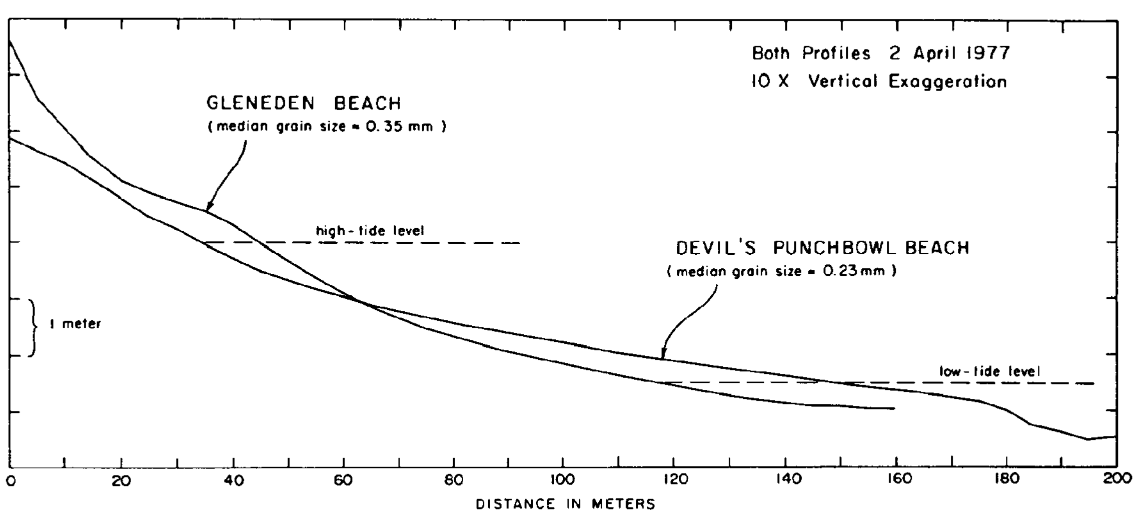


profile which is above the high-tide line). This eroded sand moves to deeper water where it accumulates in offshore bars, approximately the zone where the waves first break as they reach the coast. Sand movements reverse during the summer months of low waves, moving back onshore from the bars to accumulate in the berm. Although this cycle between two beach-profile types is approximately seasonal due to changing ocean waves, the response is really one to high storm waves versus low regular swell waves. At times, low waves can prevail during the winter and the beach berm may actually build out, although not generally to the extent of the summer berm. Similarly, should a storm occur during the summer, the beach erodes.

This cycle has been demonstrated to occur on Oregon beaches, just as along other coasts. In one study, profiles were obtained monthly during the winter of 1976-77 from two beaches, that to the south of Devil's Punchbowl at Otter Rock and that at Gleneden Beach south of Lincoln City (Aguilar and Komar 1978). These two beaches were selected because of their contrasting sand sizes, which produce marked differences in overall slopes of the profiles. The sediment grain size is the primary factor that governs the slope of a beach, the slope increasing with increasing grain size. Gravel beaches are the steepest, their slopes sometimes reaching 25 to 30 degrees, whereas the overall slope of a fine-sand beach may be only 1 to 2 degrees. This is seen in the comparison of beach profiles of Otter Rock and Gleneden Beach, figure 8, the latter being coarser and hence steeper.

The month-by-month changes in the profiles at Gleneden Beach are shown in figure 9. These profiles were obtained by using standard

Figure 8: Beach profiles from Gleneden Beach and Devil's Punchbowl Beach (Otter Rock), Oregon, illustrating that the coarser-sand beach (Gleneden) is steeper. (From Aguilar and Komar [1978])



surveying gear and by wading into the water. They do not show the offshore bars that were too deep to reach. However, these profiles do illustrate the rapid retreat of the beach as the winter season develops. The erosion began as early as October and continued through the spring. The return of sand to the berm and the buildup of the beach did not take place until April through June. The cycle of profiles at the Otter Rock beach was basically the same, at least in its timing. However, the magnitude of the change was much smaller than at Gleneden Beach. Sand elevations at Gleneden changed by as much as 2 to 3 meters (8 feet) (figure 9), while the changes at Otter Rock amounted to less than 1 meter (3 feet). This difference again can be attributed to differences in grain sizes between these two beaches. In general, the coarser the grain size of the beach sand, the larger the changes in its profile in response to varying wave conditions. The response to storms is also much faster for the coarser-grained beach: the storm waves not only cut back the coarser beach to a greater degree but also erode it at a much faster rate. Here nature goes counter to what might intuitively have been expected.

This greater response of coarser-grained beaches to storm waves is important to coastal-erosion processes since the waves are able to cut rapidly through the beach to reach homes and other structures. This fact points to the general role of the beach as a buffer between the ocean waves and coastal properties. During the summer when the beach berm is wide, the waves cannot reach the properties. Erosion is not a problem, thanks to the buffer protection offered by the beach. However, when the beach is cut back during the fall and early winter, it progressively loses its buffering ability and property erosion is more likely. If a storm strikes the coast in October, there may be enough beach to serve as a buffer so

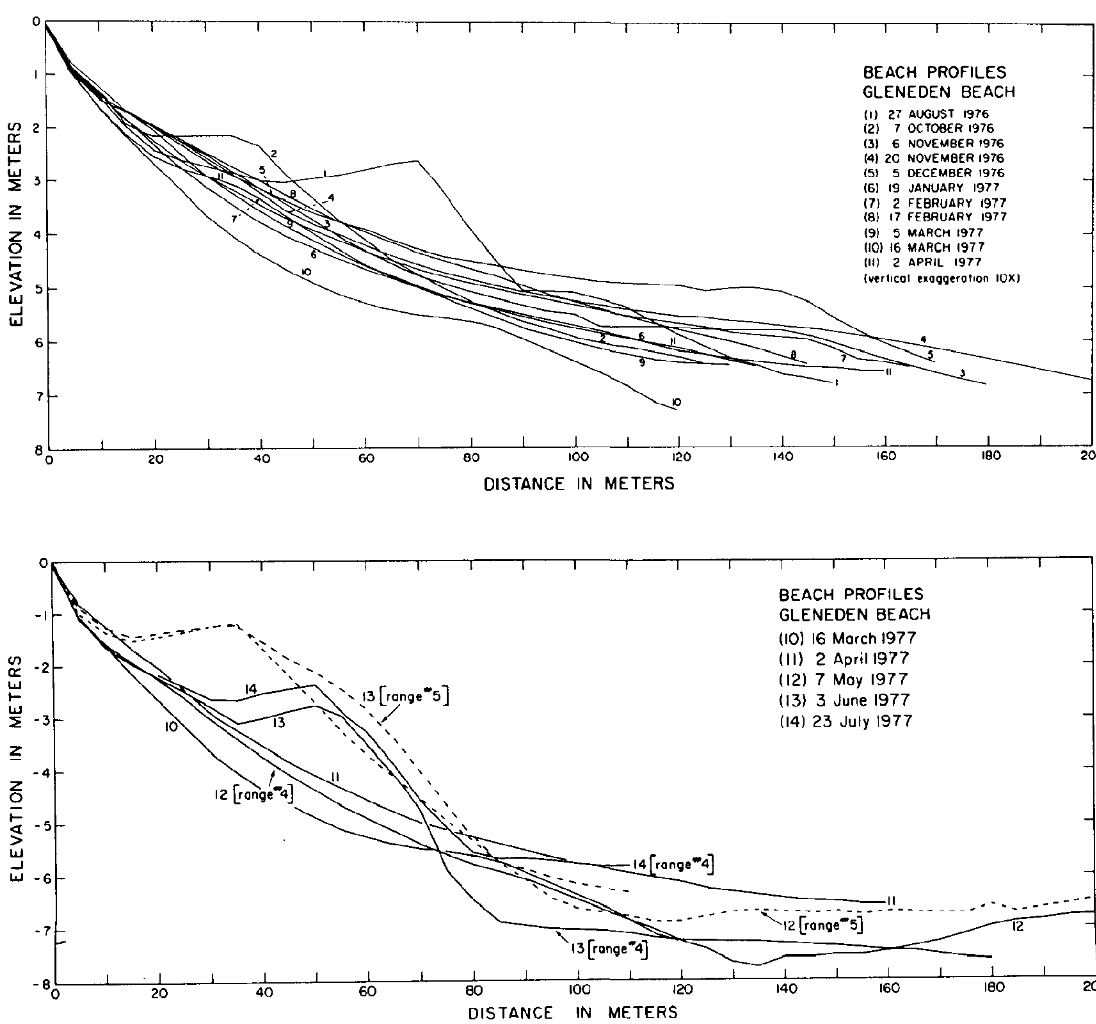


Figure 9: A series of beach profiles obtained at Gleneden Beach, Oregon, illustrating the seasonal variations for Oregon coast beaches as shown schematically in figure 7. (From Aguilar and Komar [1978])

that property erosion does not occur. It is only when the beach berm completely disappears and the waves can wash against cliffs and foredunes that the potential for property losses is great. This is often the condition from about November through March, but in fact the extent of the remnant berm is extremely variable along the coast, as is the parallel threat of property erosion. This longshore variability results from the patterns of nearshore currents which assist the waves in cutting back the beach.

Nearshore Currents and Sediment Transport

Waves reaching the coast generate currents in the nearshore zone that are important to sand movements on the beach and thus to erosion processes. These wave-generated currents are independent of ocean currents that exist farther offshore since those deep-ocean flows do not extend into the very shallow waters of the nearshore.

Most of the time waves along the Oregon coast approach the beaches with their crests nearly parallel to the shoreline. Under such circumstances the nearshore currents take the form of a cell circulation, the most prominent part of which is the seaward-flowing rip currents (figure 10). The rip currents are fed by longshore currents flowing roughly parallel to shore, but extending along only a short stretch of beach. The currents of this cell circulation are able to move sediments and thus to affect the morphology of the beach. The longshore currents hollow out troughs into the beach, generally increasing in width and depth as a rip current is approached. Rip currents can be very strong, cutting through the offshore bars to produce deeper water and a steeper but more uniform beach slope. The rips move sand offshore and thereby tend to erode crescent-shaped embayments into the beach berm. Aerial views of the coast typically show beaches that are extremely irregular, consisting of a series of rip embayments of various sizes together with troughs cut by the longshore currents and rip currents (figure 11). At times these rip-current embayments extend across the entire width of the beach and begin to cut into foredunes and sea cliffs. Such rip embayments have played a major role in property losses due to erosion. Although rip embayments seldom produce much property erosion on their own, they have the effect of eliminating the buffer protection of the beach berm. When a storm occurs, the waves are able to pass through the deep water of the rip embayment, not breaking until they reach the properties. Thus, rip embayments can control the center of attack by storm waves. The resulting erosion is commonly limited in longshore extent to only one or two hundred yards; this is the longshore span of a rip embayment that reaches the foredunes or sea cliff (figure 12).

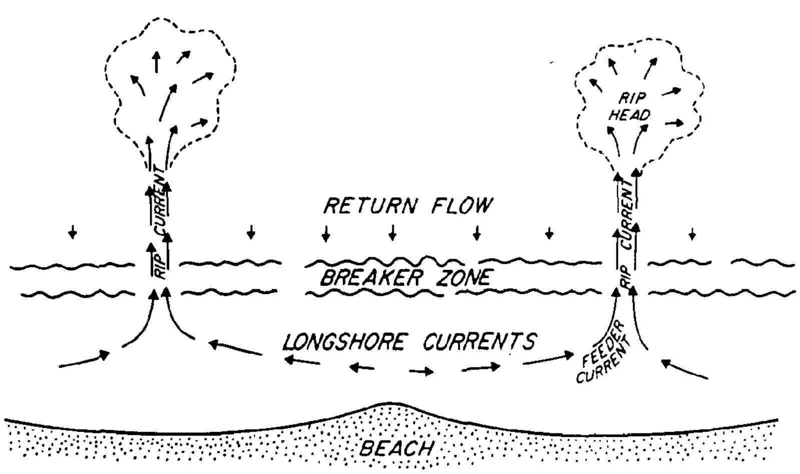


Figure 10: The nearshore cell circulation consisting of seaward-flowing rip currents and longshore currents which feed water to the rips.

When waves break at an angle to the beach, they generate a current that primarily flows parallel to the shoreline. However, even then seaward-flowing rips may be present. This longshore current, together with the waves, produces a transport of sand along the beach, a sand movement that is known as "littoral drift." This is more than a local rearrangement of the beach sand with accompanying topographical changes as produced by rip currents and the cell circulation. Instead, the littoral drift may involve along-coast movements that displace sand by many miles.

On Oregon beaches the waves tend to arrive from the southwest during the winter and from the northwest during the summer (corresponding to changes in wind directions). As a result, there is a seasonal reversal in the direction of littoral drift—north in the winter, south during the summer. The net littoral drift is the difference between these north and southward sand movements. Along most of the Oregon coast this net drift is essentially zero, at least if averaged over a number of years. This is demonstrated by the absence of continuous accumulations of sand on one side of jetties or rocky headlands, with

Figure 11: The beac along Nestucca Spit photographed durin low tide, showing th troughs and embayments eroded by longshore currents and rip currents.

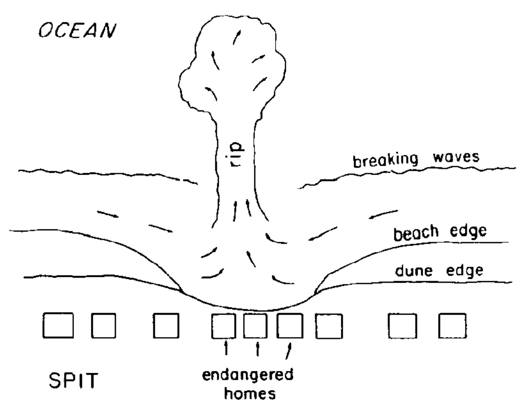


Figure 12: A schematic diagram illustrating how rip currents erode embayments that can cut through the beach and locally threaten properties.

erosion on what would be the downdrift side (Komar et al. 1976b). Patterns of sand accumulation and erosion on opposite sides of jetties, figure 13A, are found on many coasts where there is a net littoral drift. For example, along the shores of southern California and most of the east coast of the United States, erosion in the downdrift directions from jetties has caused major problems and considerable loss of property (Komar 1976, 1983b). In contrast, when jetties have been built on the Oregon coast, sand has accumulated on both their north and south sides. This pattern is diagramed schematically in figure 13B and is illustrated specifically by the Yaquina Bay jetties in figure 14. In the case of the Yaquina Bay jetties, more sand accumulated to the south than to the north, but this was due to the oblique orientation of the jetties to the overall trend of the coastline and because the prejetty shoreline curved significantly inward toward the bay. More significant is that sand accumulated both north and south of the jetties until the embayments between the jetties and the prejetty shoreline filled and an equilibrium shoreline developed. Subsequent to achieving equilibrium, there has been almost no change in the shoreline configuration. The sand that accumulated adjacent to the jetties derived from erosion of the beaches more distant from the jetties, and so an overall symmetrical pattern emerged, one that is significantly different from the asymmetrical pattern found on coasts where there is a large net littoral drift (compare figure 13A with figure 13B). This reduces the potential for major erosional and property losses due to the construction of jetties on the Oregon coast, at least compared with other coasts where there is a large net littoral drift. However, one severe erosion problem did occur on the Oregon coast in direct response to jetty construction, that which led to the destruction of the town of Bayocean (discussed below).

The Pocket-Beach Nature of the Oregon Coast and Sources of Nearshore Sands

The ultimate cause of the zero net littoral drift of sand along the Oregon coast is that the beaches are contained between rocky headlands, in effect forming pocket beaches (figure 1). The headlands are large and extend to sufficiently deep water to prevent beach sand from passing around them. Therefore, the sand within each

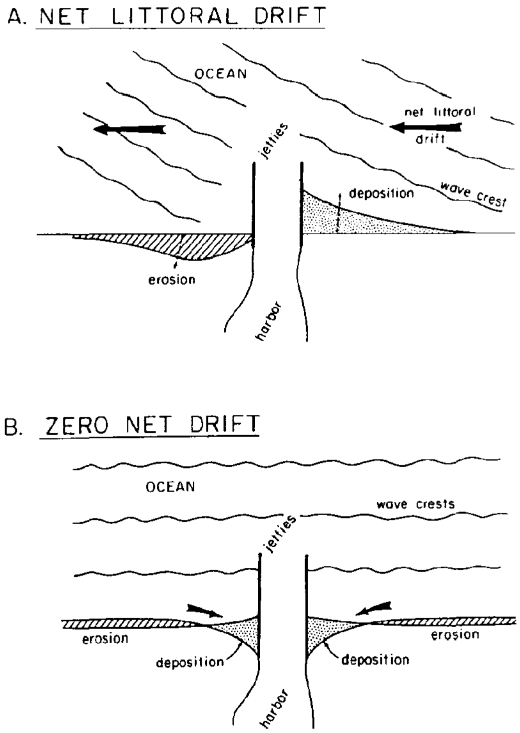


Figure 13: The patterns of sand accumulation around jetties, contrasting the condition where the jetties block a net littoral drift and the case where there is not a net littoral drift. The jetties on the Oregon coast correspond to the latter condition.

pocket beach is isolated. Sand may move north and south within a pocket because of the seasonality of the wind and wave directions, but the long-term net movement must be zero. Each of these pocket beaches on the Oregon coast can be thought of as a littoral cell. This is a useful concept in considering sources and loss of sediments on the beach, the so-called budget of littoral sediments. As will be discussed later, the patterns and magnitudes of erosion differ even from cell to cell, particularly the erosion of sea cliffs.

The one beach on the Oregon coast that does not fit this pattern of a zero-drift pocket and self-contained littoral cell is the shoreline that extends south from the Columbia River, past Seaside to Tillamook Head. This is the Clatsop Plains, formed by the accumulation of Columbia River sand, part of which moves southward until it is blocked by Tillamook Head. The bulk of sand derived from the Columbia River moves northward along the coast of Washington. The quantity of this northward sand transport can be only roughly estimated, but the primary evidence for this sand supply is that many of the beaches along the southern half of the Washington coast are growing (Phipps and Smith 1978). The highest rates of beach growth tend to be in the south closest to the Columbia River, decreasing to the north until beyond Copalis Head where net erosion prevails.

On many coastlines sand spits grow in the direction of the net littoral drift. The Long Beach peninsula extends northward from the Columbia River and likely reflects the net sand movement along the Washington coast. It is unclear whether this northward growth has continued within historic times since there have been many cycles of growth and erosion at the tip of the peninsula. There are a number of sand spits along the northern coast of Oregon, some pointing north and others pointing to the south (figure 1). Those spits are located within the beach cells where zero net littoral drift prevails, and their directions do not provide testimony as to net longshore sand movements.

Given the pocket-beach nature of the Oregon coast, the question arises as to the sources of beach sand contained within those littoral cells. These sources are reflected in the small quantities of heavy minerals contained within the beach sand. On the Oregon coast the beach sand generally consists of grains of quartz and feldspar minerals. Those particles are transparent or a light tan, and this is what governs the color of most beaches. However, the sands also contain small fractions of heavy minerals that are black, pink, various shades of green and other colors. These grains are readily apparent as specks in a handful of beach sand and are sometimes concentrated by the waves into black-sand placer deposits on the beaches. Of importance is that these heavy minerals are indicative of the rocks they came from. As a result, in many cases they can be traced to specific rocks and therefore to geographical sources. That is the case for the heavy minerals in the sands of the Oregon coast. Most distinctive are the heavy minerals derived from the Klamath Mountains of southern Oregon and northern California, eroded from a great variety of ancient metamorphosed rocks. As diagramed in figure 15, sands derived from the Klamaths contain minerals such as glaucophane, staurolite, epidote, zircon, hornblende, hypersthene, and the distinctive pink garnet which in particular can often be seen concentrated on the beach. In contrast, the rivers that drain the Coast Range transport sand that contains almost exclusively two minerals, dark-green augite and a small amount of brown hornblende (figure 15). Augite comes from volcanic rocks and is washed into the rivers by erosion of the ancient seafloor rocks uplifted into the Coast Range. The Columbia River drains a vast area that contains many types of rocks. This is reflected in the diversity of the heavy minerals in its sand (figure 15).

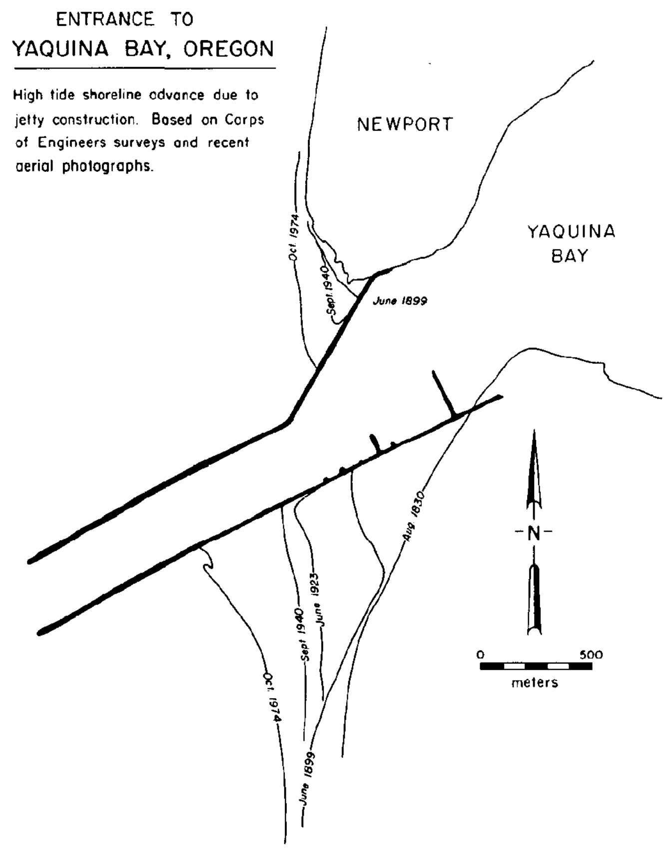
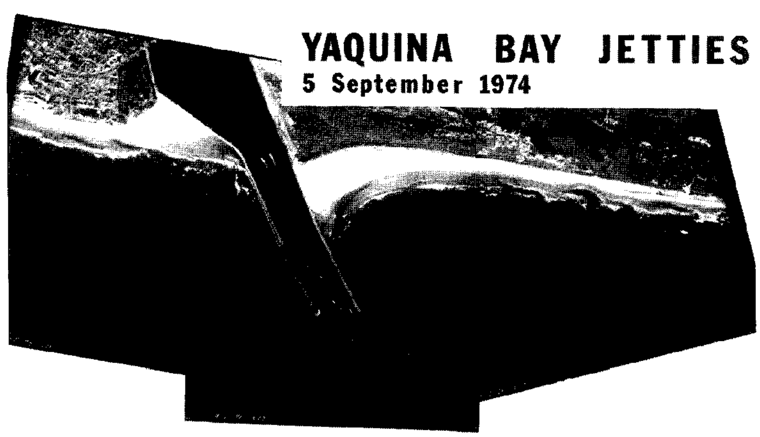


Figure 14: Compilation of shorelines at the Yaquina Bay jetties, the 1830 shoreline representing the prejetty configuration. Sand accumulated both to the north and south, but the volume to the south is greater because the embayment created between the constructed jetty and the prejetty shoreline was larger, and because the orientation of the jetties is oblique compared with the trend of the shoreline. (From Komar et al. [1976b])

The presence of sand derived from the Klamath Mountains in beaches along almost the entire length of the Oregon coast is initially surprising in view of the many headlands that prevent any longshore sand transport for that distance. However, thousands of years ago during the maximum development of glaciers, the sea level was considerably lower, and shorelines were many miles to the west of their present positions. The shoreline was then on what is now the continental shelf, and the beaches were backed by a smooth coastal plain. At that time, sand derived from rivers draining the Klamath Mountains could move northward as littoral drift without being blocked by headlands. Studies of heavy minerals contained within continental-shelf sands demonstrate that this was the case (Scheidegger et al. 1971)—the metamorphic minerals from the Klamaths can be found in the shelf sands nearly as far north as the Columbia River. As the Klamath-derived sand moved north, additional sand was contributed to the beaches by rivers draining the Coast Range; thus, there is progressively more augite and a lower proportion of metamorphic minerals from the Klamaths. The Columbia River was a source of much sediment, but most of that sand moved to the north; as a result, it dominates the mineralogy of ancient beach sands found on the Washington continental shelf. Some Columbia River sand did move south along the Oregon beaches during lowered sea levels, mixing with the sand from the Klamath Mountains and Coast Range.



The absence of headlands during lowered sea levels permitted an along-coast mixing of sands derived from multiple sources, principally from the Klamath Mountain metamorphics, the

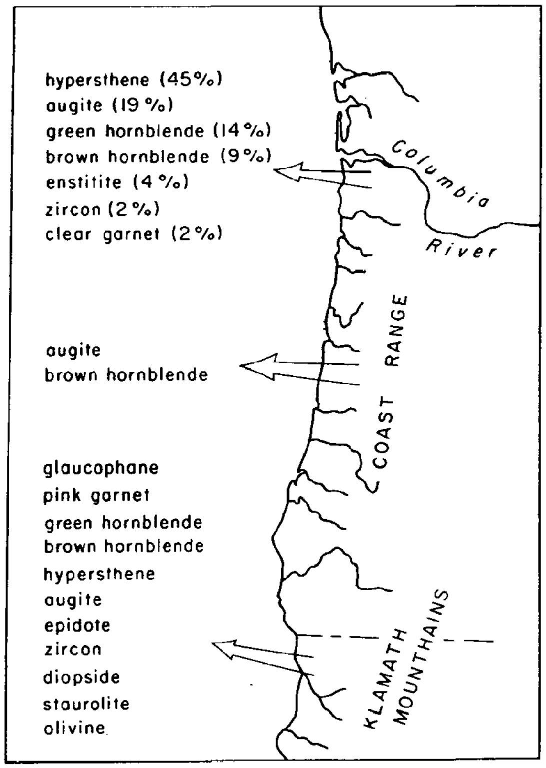


Figure 15: The principal sources of sand to Northwest beaches are the Columbia River, the Coast Range mountains, and the Klamath Mountains. Each source supplies different suites of heavy minerals to the beach and estuarine sands. (From Clemens and Komar [(1988b])

Coast-Range volcanics, and the Columbia River. Depending on the location along this former shoreline of the Oregon coast, the beach consisted of various proportions of mineral grains from these sources. Although a portion of the beach sand was left behind during the rapid rise in sea level and now can be found on the continental shelf, some of it migrated landward with the transgressing shoreline. Because the beaches would have been low in relief, storm waves were able to wash over them, transporting sand from the ocean shores to the landward sides of the beaches and thereby producing the migration. Additional sand was obtained from the various river sources and from sediments eroded from the coastal plain.

About five to seven thousand years ago, the rate of rise in sea level decreased as the water approached its present level. At about that time, the beaches of Oregon came under the influence of headlands that segmented the formerly continuous shoreline. At some stage several thousand years ago, the headlands extended into sufficiently deep water to hinder further along-coast transport of the beach sands. This is shown by a study of the mineralogy of sand found on the present-day beaches (Clemens and Komar 1988a, 1988b). The pattern of along-coast mixing of sand from the various sources, established during lowered sea levels, is still partly preserved within the series of pocket beaches now separated by headlands. Therefore, one can still find minerals derived from the Klamath Mountains in virtually all of the beaches along the Oregon coast, even though it is certain that the sand can no longer pass around the many headlands that separate those beaches from the Klamaths. In most cases, that Klamath-derived sand could have reached the modern beach only by along-coast mixing during lowered sea levels and subsequently moving onshore with the rise in the sea level at the end of the ice ages. However, there has been some modification of the beach-sand mineralogy from that along-coast mixing pattern as local sources have contributed sand to the beaches during the last few thousand years. Such beach-sand sources include sea-cliff erosion and some sand derived from rivers and streams entering the isolated pocket beaches.

There can be distinct changes in beach-sand mineralogies on opposite sides of headlands, that is, within adjacent but isolated pocket beaches or littoral cells (Clemens and Komar 1988a, 1988b). One such change is found at Cascade Head north of Lincoln City and continues at Cape Foulweather further south. To the north of Cascade Head the beach sand is rich in augite, which came either from the local rivers and streams draining the Coast Range or from sea-cliff erosion which cuts into alluvium derived from that same volcanic source. In contrast, to the south of Cascade Head the augite content of the beach sand is much reduced. Sea cliff erosion is of obvious importance there, but these cliffs are cut into a marine terrace that contains sands of ancient beaches and dunes that have been uplifted. Analyses completed on the mineralogy of those terrace sands indicate that they are also composed of mixtures of Klamath Mountain, Coast Range, and Columbia River sands (Clemens and Komar 1988a). Apparently these terrace deposits also record an along-coast mixing of sediments at lowered sea levels, a mixing that was preserved much as it has been on the modern beaches. This has an unfortunate aspect in that it makes it virtually impossible to distinguish what portion of the sand on the modern beach in that area has been contributed by recent cliff erosion and what sand moved onshore during the last rise in sea level. At any rate, the change in beach-sand mineralogy on opposite sides of Cascade Head does demonstrate the effectiveness of that headland in isolating the adjacent pocket beaches. It also shows that recent contributions to the beaches have been sufficient to alter the pattern established by along-coast mixing during lowered sea levels.

A still more dramatic change in the beach sand occurs at Tillamook Head, south of Seaside, figure 16 (Clemens and Komar 1988a, 1988b). North of this headland the beach sand is derived almost entirely from the Columbia River, and the abundant supply of sand from that large river has built the shoreline out significantly within historic times. South of the headland the beach sand is abundant in augite, again indicating a Coast Range source from local rivers or cliff erosion. This beach sand also contains small amounts of Klamath Mountain minerals, the farthest north the relict pattern of along-coast mixing during lowered sea levels can be found preserved in the modern beaches. There is some Columbia River sand in this beach to the south of Tillamook Head, but it got there by mixing southward with sands from the other sources during lowered sea level and then migrating onshore. That Columbia-derived sand has been on the beach for thousands of years, whereas to the north of the headland the beach sand came from the Columbia within the last century or two. This contrasting history of the beach sands is also indicated by the degree of rounding of the individual grains, as shown in figure 16. North of the headland the grains are fresh in appearance and angular, attesting to their recent arrival from the Columbia—the grinding action of the surf has not had sufficient time to abrade and round the grains. To the south of the headland the grains are much rounder, their sharp edges having been worn away during thousands of years of movement beneath the swash of waves on the beach.

During low stands of sea level, the coastal rivers were able to cut down their valleys. When the water rose at the end of the ice age, these valleys were drowned and developed into estuaries. These estuaries are important, serving as harbors and the centers of many coastal communities. They are also environments of

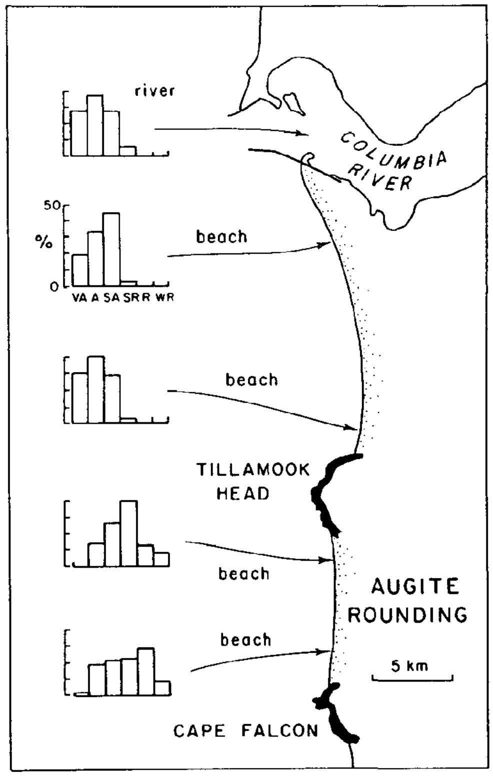


*Figure 16: Changes in the degree of rounding of the beach sand on opposite sides of Tillamook Head, with more angular grains to the north due to their recent arrival from the Columbia River (VA = very angular, A = angular, SA = subangular, SR = subrounded, R = rounded, and WR = well rounded). (*After *Clemens and Komar [1988a])*

significant fisheries, and, as will be discussed here, play a central role in sediment movements on the coast which govern contributions of sand to the beaches.

An estuary is a zone of complex mixing of fresh water from the river with salt water from the ocean. The fresh water is less dense and therefore tends to flow over the top of the seawater. At times, much of the fresh water from the river flows through the entire estuary and enters the ocean before it finally mixes with the underlying sea water. In such a case, the lens of salt water at depth within the estuary has a net flow from the ocean into the estuary. This is significant since it is one mechanism that transports sediment from the ocean into the estuary and inhibits the river sands from reaching the ocean beaches, the situation found in many Northwest estuaries.

The restriction of sand movement through Northwest estuaries was first demonstrated in a study of sediments within Yaquina Bay (Kulm and Byrne 1966). Similar to the other rivers draining the Coast Range, the Yaquina River transports sand containing augite as its principal heavy mineral. This sand contrasts with the beach sand outside of the bay that contains a large variety of minerals, including the metamorphic minerals derived from the Klamath Mountains. In addition, some of the quartz and feldspar grains on the beach are coated with red iron oxide (these grains are probably from sea-cliff erosion of the marine terraces); such coated grains are not found in the Yaquina River. These differences make it possible to trace the movement of the river and beach sands entering the estuary. The result is summarized in figure 17 from Kulm and Byrne (1966), where it is seen that the river sand (fluviatile) forms 100% of the estuarine sediment in only the landward portion of Yaquina Bay. Marine sand has been carried into the bay through the inlet and dominates the estuarine sediments near the mouth. Much of the bay is a zone where the river and marine sands are mixed in varying proportions. The results indicate that Yaquina Bay is slowly being filled with sediment—fluviatile sands from the land and marine sands from the ocean. This activity has also been shown for Alsea Bay where drilling through the sediments indicates that the bay began to fill immediately after the formation of the estuary with the last rise in sea level and is continuing to fill (Peterson et al. 1982, 1984a). Becoming filled with sediments is generally the fate of estuaries. Having developed by the drowning of river valleys at the end of the ice age, estuaries represent an environment that is out of equilibrium. As a result, an estuary tends to fill until it is reduced to a river channel that is able to transport all of its sediments to the ocean. Such a development involves thousands of years, so we should not view our estuaries as ephemeral features.

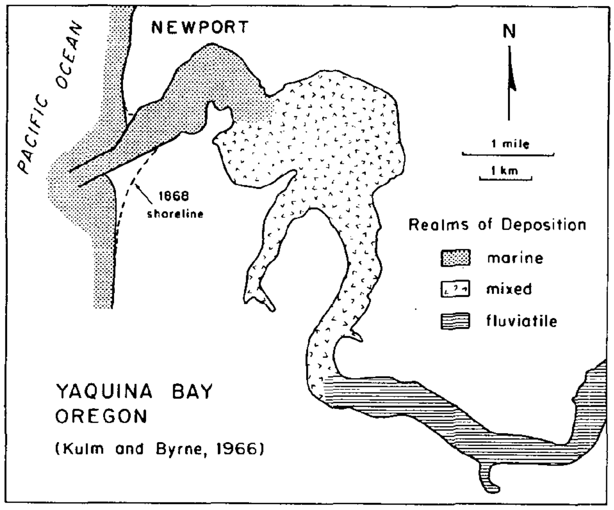


Figure 17: Sediment patterns within Yaquina Bay, illustrating the mixing of marine sands carried into the estuary by tidal flows and fluvial sands from the river. (After Kulm and Byrne [1966])

Another implication of the results in figure 17 is that little if any sand from the Yaquina River is currently reaching the ocean beach. This conclusion applies only to sand-sized grains. The fine clays that remain in suspension in the water are carried into the ocean. Their presence is evident by the brown plumes that emanate from the inlet during river floods. Most of the major coastal rivers are separated from the ocean by large estuaries and thus are not likely to contribute a significant amount of sand to the modern beaches. This in part explains why many of the Oregon beaches have a relatively small volume of sand and why their mineralogies still reflect the along-coast mixing of sand sources during low stands of sea level rather than more recent contributions.

Such patterns of sand deposition have been shown to occur for other major estuaries of the Northwest (Scheidegger and Phipps 1976; Peterson et al. 1984). However, a study of the small Sixes River of Oregon, which does not really have an estuary, indicates that it supplies sand to the adjacent beach, although the amounts would be minor given the small size of that river (Boggs 1969; Boggs and Jones 1976). In general, the major rivers have sufficiently large estuaries that it is doubtful whether much, if any, river sand reaches the adjacent beaches. The one clear exception to this is the Columbia River, which transports more than 100 times as much sand as the next largest river (the Umpqua) and on the order of 1,000 times as much sand as other coastal rivers (Clemens and Komar 1988a).

Case Studies of Sand Spit Erosion

The most dramatic occurrences of erosion on the Oregon coast have centered on the sand spits. The causative factors have ranged from jetty construction at Bayocean Spit, to the natural processes of waves and currents at Siletz and Nestucca Spits, to extreme examples of erosion at Alsea and Netarts Spits initiated during the 1982-83 El Niño.

Jetty Construction and the Erosion of Bayocean Spit

The story of Bayocean Spit is of particular interest in that it provides the earliest example on the Oregon coast of a failed attempt at major development and also of the erosive impacts associated with jetty construction (Terich and Komar 1974; Komar and Terich 1976). The San Francisco realtor T.B. Potter was attracted to Tillamook Bay during a fishing trip in 1906 and vowed to build the "Atlantic City of the Pacific Coast" on the spit separating the Bay from the ocean. His vision soon took form with the construction of an elegant hotel, a natatorium that housed a heated swimming pool with artificial surf, a number of permanent homes, and a "tent city" for summer visitors. The downtown contained a grocery, bowling alley, and agate shop. However, the development soon ran into economic problems as lots did not sell at the hoped for rate, primarily because of the inaccessibility of the area and delays in construction of the railroad from Portland. But the chief threat came from erosion caused by jetty construction in 1914-17 at the mouth of Tillamook Bay (figure 18). Because of economic constraints, only a north jetty was completed at that time (the south jetty was not built until 1974), and this turned out to be critical to the magnitude of the resulting erosion. The overall pattern of sand movement and shoreline changes was similar to that depicted schematically in figure 13B, but it was made more complex by the fact that only one jetty was constructed. Sand quickly accumulated north of the jetty, figure 18, with the shoreline building out. At the same time, sand accumulated to the south but formed a shoal within the mouth of the inlet, greatly increasing the hazards to navigation. The sand that formed the shoal was derived from erosion along the length of Bayocean Spit. It is likely that some of the sand brought to the shoal was carried into the bay and perhaps to the offshore, so that erosion of Bayocean Spit continued for many years rather than reaching a new equilibrium as is possible where two jetties are constructed (figure 13B). The erosion of Bayocean was most rapid during the 1930s and 1940s following reconstruction and lengthening of the north jetty. The ocean edge of the spit

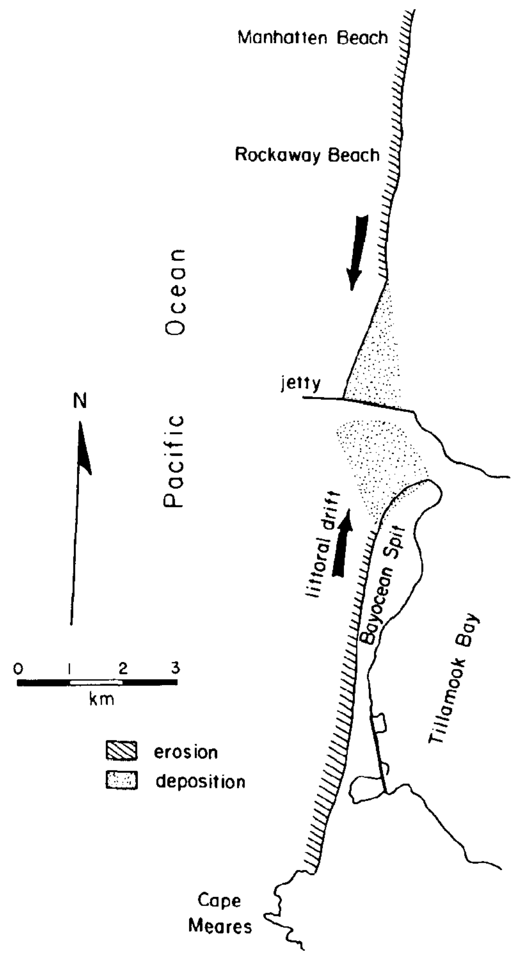


Figure 18: Schematic diagram illustrating the patterns of erosion and accretion in response to construction of the north jetty at the inlet to Tillamook Bay. Sand that came from erosion along the length of Bayocean Spit accumulated to form an extensive shoal at the mouth of the inlet.

retreated, dropping houses, the natatorium (figure 19), and finally the hotel into the surf. A storm during November 1952 brought the final demise of the development, breaching the spit at its narrowest point. This breach was diked by the Corps of Engineers in 1956, rejoining what had become an island to the mainland. All that remains of Potter's development are slabs of concrete foundations that now litter the beach.

Natural Processes and the Erosion of Siletz and Nestucca Spits

The erosion of Siletz and Nestucca Spits provides examples of the impacts of natural processes—the combined effects of storm waves, rip currents and elevated water levels (Komar and Rea 1976; Komar and McKinney 1977; Komar 1978, 1983a). The development of Siletz Spit began in the 1960s with the construction of a number of homes, many within foredunes immediately backing the beach. The first major episode of erosion leading to property losses

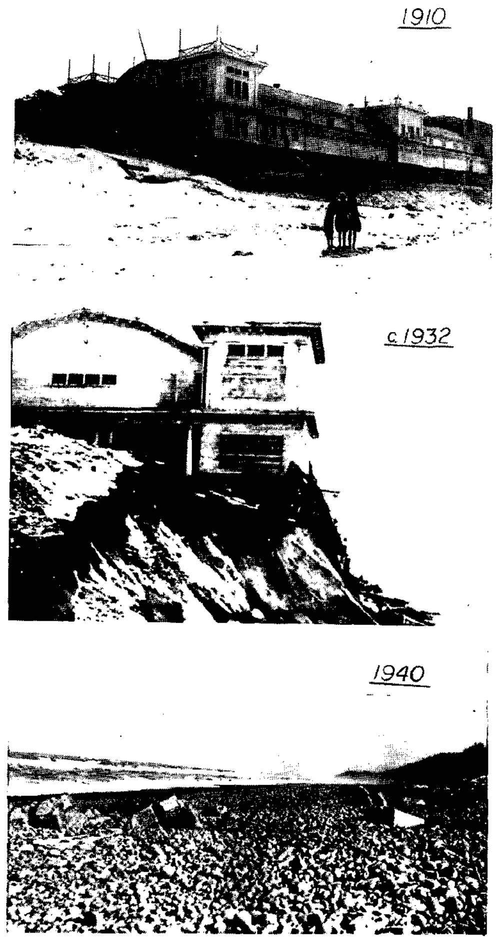


Figure 19: The progressive erosional destruction of the Natatorium on Bayocean Spit. (Photos from The Tillamook Pioneer Museum)

occurred during the winter of 1972-73. One house under construction was lost, figure 20, while others ended up on promontories extending into the surf zone when riprap was first installed along their seaward fronts and then on their flanks as adjacent empty lots continued to erode. The main factor in that erosion episode was the occurrence of major storm waves, the 23-foot significant wave heights of December 1972 in the microseismometer record of figure 5. However, the erosion was limited to only a small portion of the spit, determined by the presence of a rip current that had hollowed out an embayment in the beach so that waves were able to reach the foredunes and houses (figure 21). A series of aerial photographs of Siletz Spit revealed the repeated occurrence of such erosion events over the years. In general, during any particular winter the erosion would occur in only one or two locations determined by the largest rip-current embayments. In subsequent winters the erosion shifted to other areas as the rip currents changed positions (we do not know what controls the location of rip currents and therefore cannot predict where the erosion will occur). In the meantime, earlier "bites" taken out of the foredunes by rip currents and storm waves would fill in with drift logs which in turn captured wind-blown sands so the dunes quickly reformed. This cycle of dune erosion and reformation occurred repeatedly on Siletz Spit, with no measurable long-term net retreat of the seaward edge of the foredunes on the spit. The principal mistake made in developing Siletz Spit was to build homes in this zone of foredunes susceptible to periodic erosion. We quickly became aware of this during the erosion of 1972-73 (figure 20)—the erosion exposed drift logs within the heart of the spit, often beneath homes built in the 1960s. These drift logs had been cut by saws. What clearer indication could one have of the ephemeral nature of the sites where these homes had been built?

Figure 20: Erosion on Siletz Spit during December 1972. One house under construction was lost, while others ended up on promontories of riprap extending into the surf as adjacent empty lots were left to erode.

Siletz Spit has repeatedly eroded during subsequent winters, but each time more riprap has been added so that the properties are now reasonably secure. Lots lost to erosion have been filled with beach sand and leased again for development.

Large storm waves combined with high spring tides during February 1978 to cause extensive erosion in many areas of the Oregon coast (Komar 1978). The greatest impact occurred along Nestucca Spit on the northern Oregon coast, where an uninhabited area of the spit was breached and foredune erosion threatened a new development in which houses were still under construction (figures 22 and 23). Storm waves again combined with rip-current embayments to control the zones of maximum erosion along the spit and determine the area of breaching. However, of particular importance to the erosion was the simultaneous occurrence of high perigean spring tides and a storm surge which raised water levels by some 8 to 9 inches above predicted tide levels. Spring tides occur when the moon, earth, and sun line up so the gravitational forces causing the tide superimpose, producing the highest monthly tides. A perigean spring tide occurs when the moon comes closest to the earth in its eliptical orbit, so that the tide-producing force is still greater than during normal spring tides. Typical spring tides on the Oregon coast reach +9 feet MLLW, while perigean spring tides achieve +10 feet MLLW (MLLW denotes "mean lower low water," the average of the lowest daily tides, which is taken as the 0 reference tidal elevation). Measured high tides reached +10.2 feet MLLW at the time of the February 1978 storm that eroded Nestucca Spit, unusually high for the Oregon coast and substantially higher than tides during the December 1972 erosion of Siletz Spit. It was this

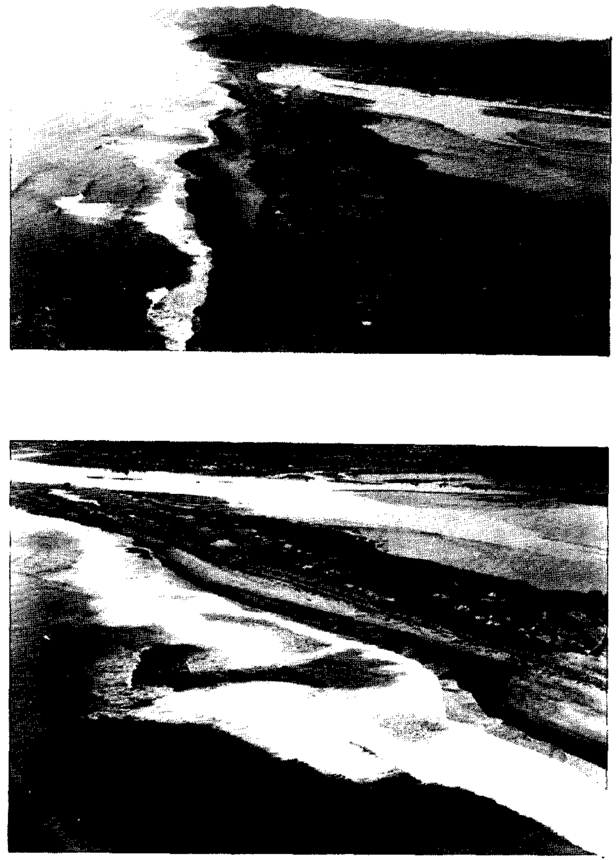


Figure 21: Rip currents cutting embayments through the beach and reaching the development on Siletz Spit during December 1972. The large embayment seen in the upper photograph was the center of property losses photographed in figure 20.

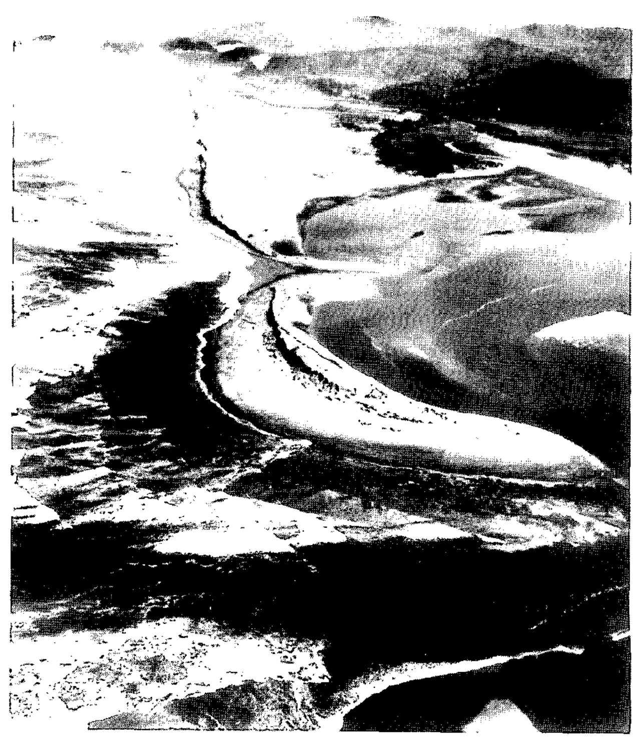


Figure 22: The breaching of Nestucca Spit during the February 1978 storm at a time of perigean spring tides. (Photo from Oregon State Highway Department)

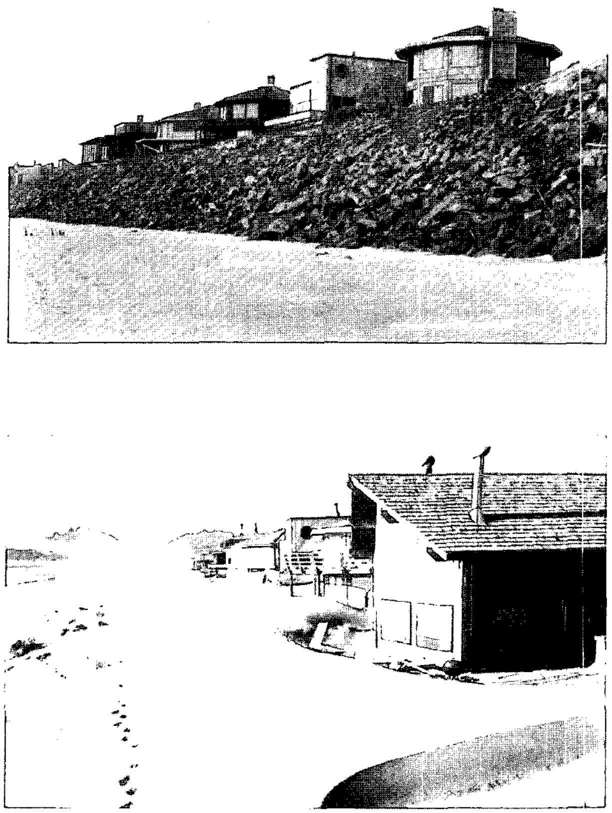


Figure 23: (Upper) *Riprap placed to protect homes under construction at Kiwanda Shores on Nestucca Spit in response to erosion during February 1978.* (Lower) *The subsequent accumulation of dune sands, completely covering the riprap and becoming a problem for the homes (1988 photo).*

combination of a major storm and perigean high tides that resulted in the unusual occurrence of breaching at Nestucca Spit. The only other spit breaching known to have occurred during historic times was at Bayocean Spit, and that breach was due to jetty construction rather than natural causes. There are frequent occurrences of breaching and washovers on spits and barrier islands of the east and Gulf coasts of the United States due to the subsidence of those areas adding to the global rise in sea level. However, the Northwest coast is rising tectonically, so there is minimal transgression of the sea over the land, and this probably accounts for the rarity of spit breaching here. It took the unusual circumstances of the February 1978 storm to produce a breach—high perigean spring tides with a significant storm surge, exceptionally energetic storm waves, and the development of a major rip-current embayment that by chance focused the erosion along the thinner section of the spit.

When the storm struck in February 1978, a development of new houses was under construction on the foredunes at Kiwanda Beach at the north end of Nestucca Spit (figure 23, *upper*). Like the erosion of Siletz Spit, drift logs were exposed within the eroding dunes, some of which had been sawed. However, these logs were more rotten than those found within Siletz Spit, suggesting that erosion episodes on Nestucca Spit are less frequent. This lower frequency of erosional occurrences at Nestucca Spit is probably due to its beach being finer grained than at Siletz; as I explained earlier, coarser-sand beaches respond more rapidly and to a greater degree to storm-wave conditions. Nestucca Spit began to mend during the summer following its erosion. As was the case with the dune reformation on Siletz Spit, drift logs accumulated within the breach and helped to trap wind-blown sand. So much sand has returned to the beach fronting the housing development at Kiwanda Beach that the masses of riprap are now buried and the overabundance of sand has become a problem (figure 23, *lower*).

The 1982-83 El Niño—An Unusual Erosion Event

A decade ago, an El Niño was thought to involve only a shift in currents and a warming of ocean waters to the west of South America. Its occurrence was primarily of interest because an El Niño caused the mass killing of fish off the coast of Peru. No one imagined that an El Niño had wide-ranging consequences, including playing a major role in beach erosion along the west coast of the United States. This awareness came during the El Niño of 1982-83, an event of unusual magnitude, when erosion problems were experienced along the shores of California and Oregon. The natural processes usually involved in beach erosion also played a role during the 1982-83 El Niño, but generally at much greater intensities than normal. In addition, there were unusual effects that enhanced the overall erosion problems and caused them to continue well beyond 1982-83.

It once was thought that the onset of El Niño off Peru was caused by the cessation of local coastal winds which produce upwelling. This view changed when it was demonstrated that these local winds do not necessarily diminish during an El Niño; rather, it is the breakdown of the equatorial trade winds in the central and western Pacific that triggers an El Niño. During normal periods of strong southeast trades, there is a sea-level setup in the western equatorial Pacific with an overall east-to-west upward slope of the sea surface along the equator. The same effect is obtained when you blow steadily across a cup of coffee—the surface of the coffee becomes highest on the side away from you. If you stop blowing, the coffee surges back and runs up your side of the cup. The process is similar in the ocean when the trade winds stop blowing during an El Niño. The potential energy of the sloping water surface is released, and it is this release that produces the eastward flow of warm water along the equator toward the coast of Peru, where it kills fish not adapted to warm water. Associated with this movement of warm water eastward along the equator is a wavelike bulge in sea level. The Coriolis force, which results from the rotation of the earth on its axis, causes currents to turn to the right in the northern hemisphere and to the left in the southern hemisphere. Since this released water during an El Niño flows predominantly eastward along the equator, the Coriolis force acts to confine the wave to the equatorial zone, constantly turning it in toward the equator. This prevents the dissipation of the sea-level high by its expansion to the north and south away from the equator. The eastward progress of the sea-level wave can be monitored at tide gauges located on islands near the equator (Wyrtki 1984). As discussed earlier, measurements from a tide gauge can be averaged so as to remove the tidal fluctuations, yielding the mean sea level for that period of time. Sea-level variations at islands along the equator during the 1982-83 El Niño are shown in figure 24. From these tide-gauge records one can easily envision the passage of the released sea-level wave as it traveled eastward across the Pacific. Its crest appears to have passed Fanning Island south of Hawaii in late August and Santa Cruz in the Galapagos at the end of the year, and reached Callao on the coast of Peru in January 1983. The water-level changes associated with these sea-level waves during an El Niño are very

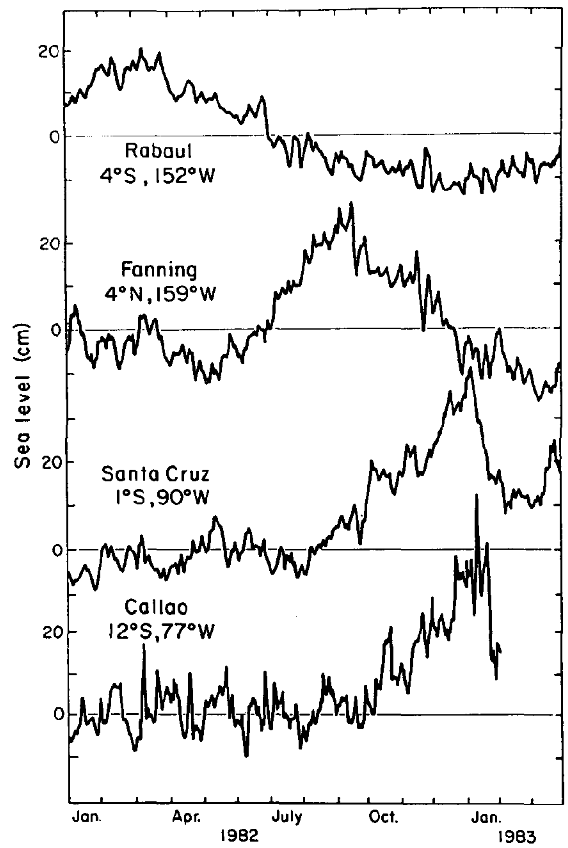


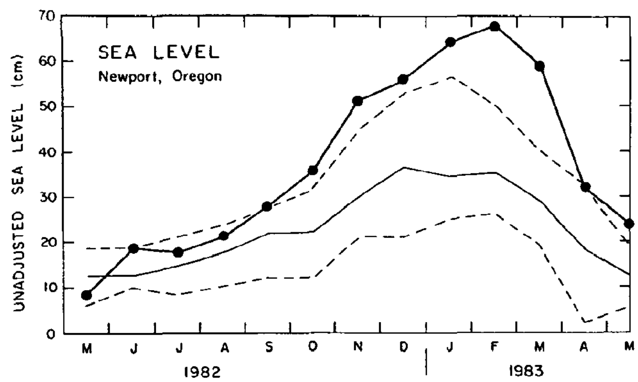
Figure 24: The sea-level "wave" during the 1982-83 El Niño measured at a sequence of islands from west to east near the equator, and finally at Callao on the coast of Peru. (After Wyrtki [1984])

large (figure 24). They typically involve variations up to 50 centimeters (20 inches) and take place within a relatively short period of time, 4 to 6 months. Translated into an annual variation, this is equivalent to a rate of approximately 1,000 millimeters a year, far in excess of the 1 to 2 millimeters a year global rise in sea level caused by the melting of glaciers.

With its arrival on the coast of South America, the sea-level wave splits, and the separated parts respectively move north and south along the coast. Now the wave is held close to the coast by the combined effects of the Coriolis force and refraction of the wave over the inclination of the continental slope. This again prevents the sea-level high from flowing out to sea and dissipating. Analyses of tide-gauge records along the coast have demonstrated that sea-level waves can travel as far north as Alaska (Enfield and Allen 1980). The analyses have also shown that as the sea-level wave travels northward, it loses relatively little height at the coastline itself. The Coriolis force increases in strength at higher latitudes, so the wave hugs the coast more tightly and thereby maintains its height, even though it may lose some of its energy. The wave travels at a rate of about 50 miles a day, and so quickly reaches California and Oregon following its inception at the equator. The water-level changes associated with these shelf-trapped sea-level waves are an important factor in beach erosion along the west coast of North America during an El Niño.

In summary, one aspect of an El Niño is the generation of large sea-level variations which take the form of a wave that first moves eastward along the equator and then splits into poleward-propagating waves when it reaches the eastern margin of the Pacific Ocean. These basinwide responses involve several months of wave travel, and at any given coastal site the sea-level wave may significantly raise water levels for several months.

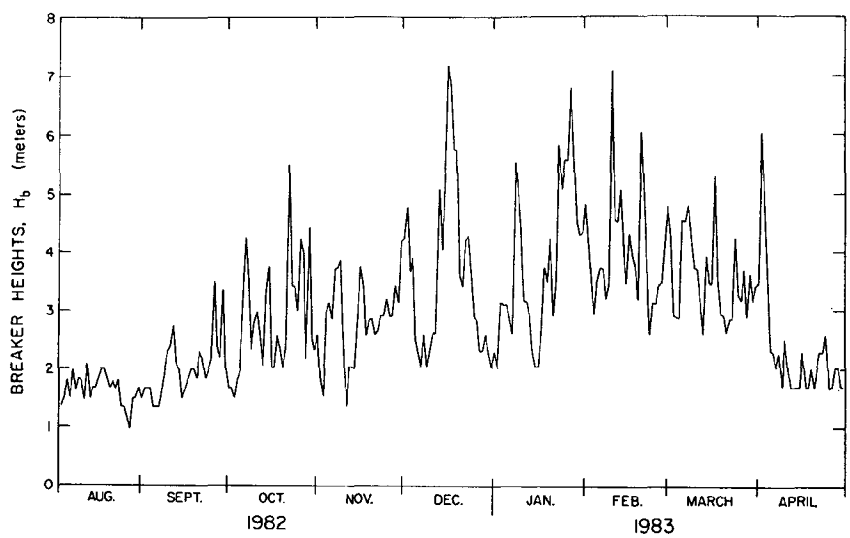
Figure 25 shows the monthly mean sea levels measured by the tide gauge in Yaquina Bay during the 1982-83 El Niño (Huyer et al. 1983; Komar 1986). Sea level reached a maximum during February 1983, nearly 60 centimeters (24 inches) higher than the mean water surface in May 1982, nine months earlier. The thin solid line in the figure follows the ten-year means for the seasonal variations, and the dashed lines give the previous maxima and minima measured in Yaquina Bay. These curves in part reflect the normal seasonal cycle of sea level produced by parallel variations in atmospheric pressures and water temperatures. However, it is apparent that the 1982-83 sea levels were exceptional, reaching some 10 to 20 centimeters higher than previous maxima, about 35 centimeters (14 inches) above the average winter level. Much of this unusually high sea level can be attributed to the effects of a coastally trapped sea-level wave generated by the El Niño.



Wave conditions on the Oregon coast were also exceptional during the 1982-83 El Niño (Komar 1986). Figure 26 shows the daily measurements from the microseismometer at Newport, collected from August 1982 through April 1983. There were several storms that generated high-energy waves, three achieving breaker heights on the order of 20 to 25 feet.

Figure 25: (Above) *Monthly sea levels measured with the tide gauge in Yaquina Bay. The record from the 1982-83 El Niño year (dots) shows that water levels exceeded all previous records (mean values given by the solid curve, the previous maxima and minima by the dashed lines). (From Huyer et al. [1983] and Komar [1986])*

Figure 26: (Right) *Wave breaker-height measurements from Newport during the 1982-83 El Niño period. (From Komar [1986])*



The erosion which occurred on the Oregon coast during the 1982-83 El Niño was in response to these combined processes. The large storm waves that struck the coast arrived at the same time as sea level was approaching its maximum (figures 25 and 26). High spring tides were also a factor. During the December 1982 storm, high tides reached +11.0 feet MLLW, 23 inches higher than the predicted level due to the raised sea level. The tides during the January 1983 storm were still more impressive, reaching +12.4 feet, 34 inches higher than predicted. This pattern continued during the February 1983 storm when high tides up to +10.3 feet were measured, 17 inches above the predicted level. All of these high tides represent exceptional water elevations for the coast of Oregon.

As expected, the intense storm activity and high water levels during the winter of 1982-83 cut back the beaches of the Oregon coast. However, for a time the patterns of erosion were puzzling. There were numerous reports of erosion problems along the coast, yet beaches in other areas were building out. It took some time to determine what was happening. As discussed earlier, the summer waves normally approach from the northwest while the winter waves arrive from the southwest, so there is a seasonal reversal in sand transport directions along the beaches. Over the years there is something of an equilibrium between the north and south sand movements within any pocket, yielding a long-term zero net littoral drift. This equilibrium condition was upset during the 1982-83 El Niño because of the southward displacement of the storm systems. The waves approached the Oregon coast from a more southwesterly direction, and this, together with the high wave energies of the storms, caused an unusually large northward movement of sand within the beach cells (figure 27). The resulting effect was one of sand erosion at the south end of each pocket beach and deposition at the north. This can be viewed as the reorientation of the pocket beaches to face the waves arriving from the southwest, or as any one headland acting like a jetty so that it blocks sand on its south and causes erosion to its immediate north. This pattern is illustrated in figure 28 for the beaches north and south of Yaquina Head. North of that

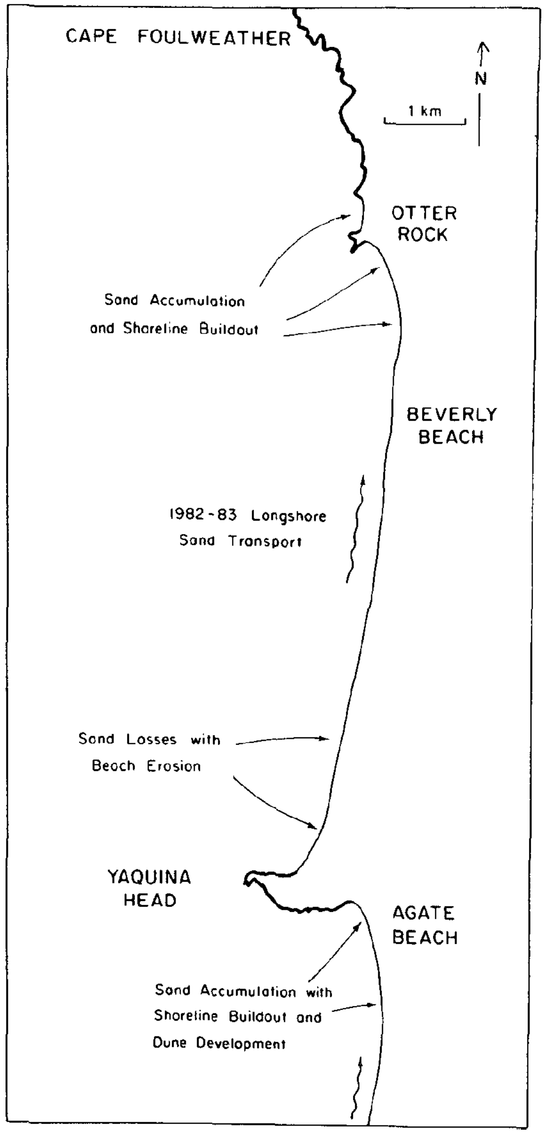


Figure 27: The patterns of beach erosion and accretion during the 1982-83 El Niño, resulting from the northward transport of sand within the littoral cell. (From Komar [1986])

headland the beach eroded down to bedrock (figure 28 *upper*), while south of it at Agate Beach so much sand accumulated it formed a large field of dunes (figure 28 *lower*). People who had the misfortune to live north of the headlands, at the south ends of the pocket beaches, experienced some of the greatest beach and property losses along the coast. There the beaches eroded to a greater degree than during normal winters, the sand not only moving offshore to form bars, but also northward along the shore. Having lost the buffering protection of the fronting beaches,

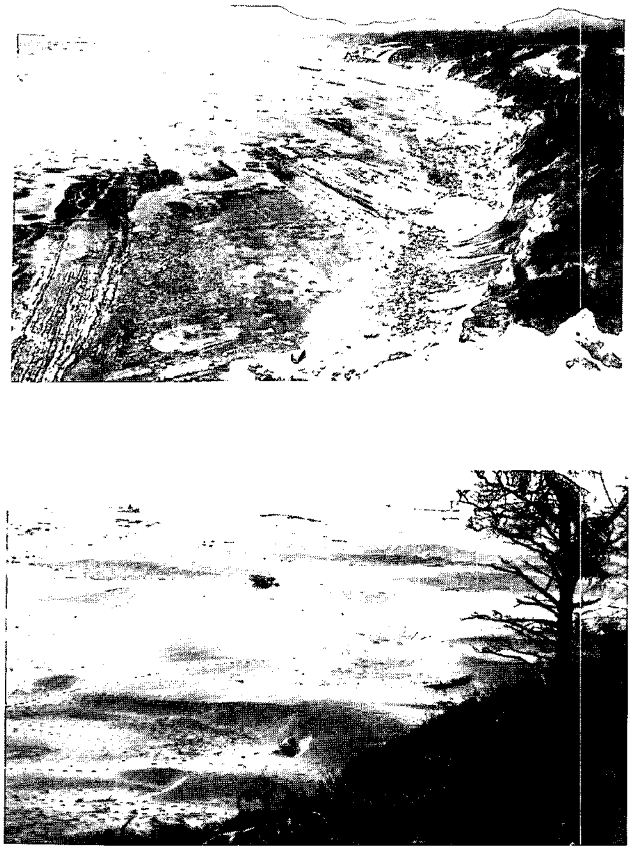


Figure 28: Beaches north and south of Yaquina Head during the 1982-83 El Niño, with a total depletion of sand to the north (upper) *and large quantities of sand accumulated to the south on Agate Beach* (lower).

properties north of headlands suffered direct attack by storm waves, in many areas resulting in considerable erosional losses.

The area that suffered the greatest erosion during the 1982-83 El Niño was Alsea Spit on the central-Oregon coast (Komar 1986). The erosion there was mainly in response to the northward longshore movement of beach sand, a movement which deflected the inlet to Alsea Bay. Although the problem originated during the 1982-83 El Niño, the erosion continued for several years due to the disruption from normal conditions. During normal periods, the channel from Alsea Bay continues directly seaward beyond the inlet mouth, but during the 1982-83 El Niño this channel was deflected well to the north, as seen in the photograph in figure 29. There was little migration of the inlet mouth itself, the deflection instead taking place in the shallow offshore. Apparent in this photograph is an underwater bar extending from the south, covered with breaking waves. The bar grew as a result of the northward sand transport during El Niño. It was the northward growth of this bar that diverted the channel from its normal course.

The erosion experienced on Alsea Spit, which continued for about three years, can be directly attributed to this northward deflection of the channel. The earliest property losses on the spit were during the winter of 1982-83 and occurred on its ocean side well to the north of the inlet. The focus of this erosion was directly landward of where the channel turned toward the sea around the end of the northward-extending offshore bar. Erosion there appeared to be caused by the over-steepened beach profile leading into the deep channel, and by direct wave attack—waves passing through this channel did not break over an offshore bar, and therefore retained their full energy until breaking directly against the properties on the spit. The erosion continued for more than three years with losses of property as the deflected channel slowly migrated southward towards its more-normal position. The photograph of figure 29 was obtained during July 1985, by which time significant migration had already taken place from the most northerly position of the opening during the winter of 1982-83. With this slow southward movement of the opening, the focus of maximum erosion on the spit similarly shifted south. In September 1985 there was an abrupt

Figure 29: The deflection of the channel leading into Alsea Bay by the northward growth of the longshore bar in response to the 1982-83 El Niño-related storm waves arriving from the southwest. (From Komar [1986])

increase in the rate of erosion as the focus was then on the unvegetated, low-lying tip of the spit seen in figure 29. Within a couple of weeks, this tongue extension of Alsea Spit completely eroded away. At the same time, the deep water of the offshore channel shifted landward, directly eroding the developed portion of the spit where it curves inward toward the inlet. Seven houses were threatened by this erosion, particularly one that was adjacent to an empty lot initially left unprotected (figure 30).

The beach fronting Alsea Spit grew significantly during the summer of 1986, and the tongue of sand began to reform at the end of the spit. Erosion during the winter of 1986-87 was minimal, so that Alsea Spit and the inlet to the bay finally returned to their normal configurations, those which had prevailed for many years prior to the 1982-83 El Niño.

The effects of the 1982-83 El Niño persisted still longer in the erosion of Netarts Spit (Komar et al. 1988; Komar and Good 1989). That erosion has been of particular concern in that its impact has been in Cape Lookout State Park, a popular recreation site. Netarts Spit forms most of the stretch of shore between the large Cape Lookout to the south and Cape Mears to the north (figure 31). Erosion of Netarts Spit during historic times had been minimal. In the late 1960s a seawall was constructed at the back of the beach in the park area. Its construction was not entirely a response to wave-erosion problems, but in part to people walking on the dune face and causing renewed activity of sand movement by winds. Therefore, the sudden and dramatic erosion during the 1982-83 El Niño came as a surprise. Being one of the smallest of the littoral cells on the coast, the pocket beach within the Netarts cell underwent a marked reorientation due to the southwest approach of waves during the El Niño. This depleted the beach of sand to the immediate north of Cape Lookout, leading to erosion of the low-lying sea cliffs and sand dunes in that area. However, of more lasting significance is that much of the sand transported northward along the beach was apparently swept through the tidal inlet into Netarts Bay; perhaps some moved offshore as well. This effectively removed the sand from the nearshore zone, leaving the beach depleted of sand and thus less able to act as a buffer between park properties and storm-erosion processes. Because of this, erosion problems on Netarts Spit have been endemic in recent years

Figure 30: Erosion of Alsea Spit as a result of inlet deflection during the 1982-83 El Niño. (From Komar (1986])

Figure 31: Netarts Spit and the inlet to Netarts Bay, with Cape Lookout in the background (March 1978, Oregon State Highway Department).

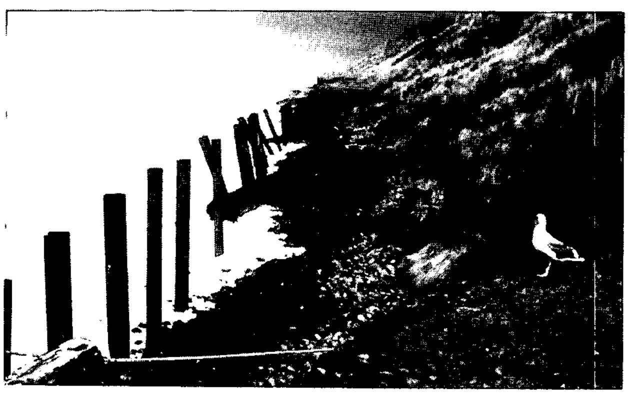


Figure 32: The progressive erosion of Cape Lookout State Park following the 1982-83 El Niño. (Upper) *The destruction of the log bulkhead and initiation of dune erosion during October 1984.* (Lower) *Erosion during the winter of 1988, leaving a beach composed of cobbles and gravel rather than sand, and the I-beams of the log bulkhead at midbeach. (From Komar et al. [1988])*

and have continued even though the direct processes of the 1982-83 El Niño have ceased.

Rip currents and storm waves have been the chief agents of erosion on Netarts Spit. They cut back the beach in the park area so that much of it was covered by exposed cobbles rather than sand (figure 32). The seawall was destroyed, so that erosion of parklands became substantial. State Parks officials have considered placing riprap to prevent additional losses of parklands. However, in subsequent winters the rip currents could be positioned in other areas along the spit, causing erosion there. The more fundamental problem is the depleted volume of sand on the beach. To solve this, officials have considered a beach nourishment project, the placement on the beach of sand brought in from some other location. Sand nourishment would restore the beach along its full length, both in its ability to act as a buffer and in its recreational uses. Possible sources of sand for such a nourishment project might be from the yearly dredging by the Corps of Engineers of Tillamook Bay or the Columbia River. A more logical source would be from dredging sandy shoals in Netarts Bay in that this would in effect return to the beach sand which had been swept into the bay, some of it during the 1982-83 El Niño. An associated positive effect would be the restoration of the bay itself, which has undergone considerable shoaling. However, Netarts Bay contains many acres of protected wetlands and has the highest diversity of clam species of any Oregon estuary. Accordingly, dredging and sand removal would have to be balanced against the probable negative impacts of such operations in the bay.

Processes and Patterns of Sea-Cliff Erosion

The erosion of sea cliffs is a significant problem along many of the world's coastlines, including those of Oregon (figure 33). Most communities along the Oregon coast are built on uplifted marine terraces or on alluvial slopes emanating from the nearby Coast Range. These elevated lands are subject to erosion along their ocean margins with the formation of cliffs. State lands are also being lost as cliff erosion takes place in coastal parks and affects state highways.

Considering the extent and importance of sea-cliff erosion, it is surprising how few studies have focused on this problem, at least in comparison with beach-erosion problems and processes. Part of the reason for this is the inherent difficulty in accounting for the multitude of factors that can be involved in cliff erosion (figure 34). One of the most problematic aspects is the cliff itself—its material composition and its structure, including bedding stratification (horizontal or dipping) and the presence of joints and faults. These factors are important in determining whether the cliff retreat takes the form of abrupt large-scale landsliding or the more continuous failure of small portions of the cliff face. The processes of cliff attack are also complex. The retreat may be caused primarily by groundwater seepage and direct rain wash, with the ocean waves acting only to remove the accumulating talus at the base of the cliff. In other locations the waves play a more active role, directly attacking the cliff and cutting away its base.

Figure 33: Sea cliff erosion in Lincoln City, threatening old homes and recently built condominiums.

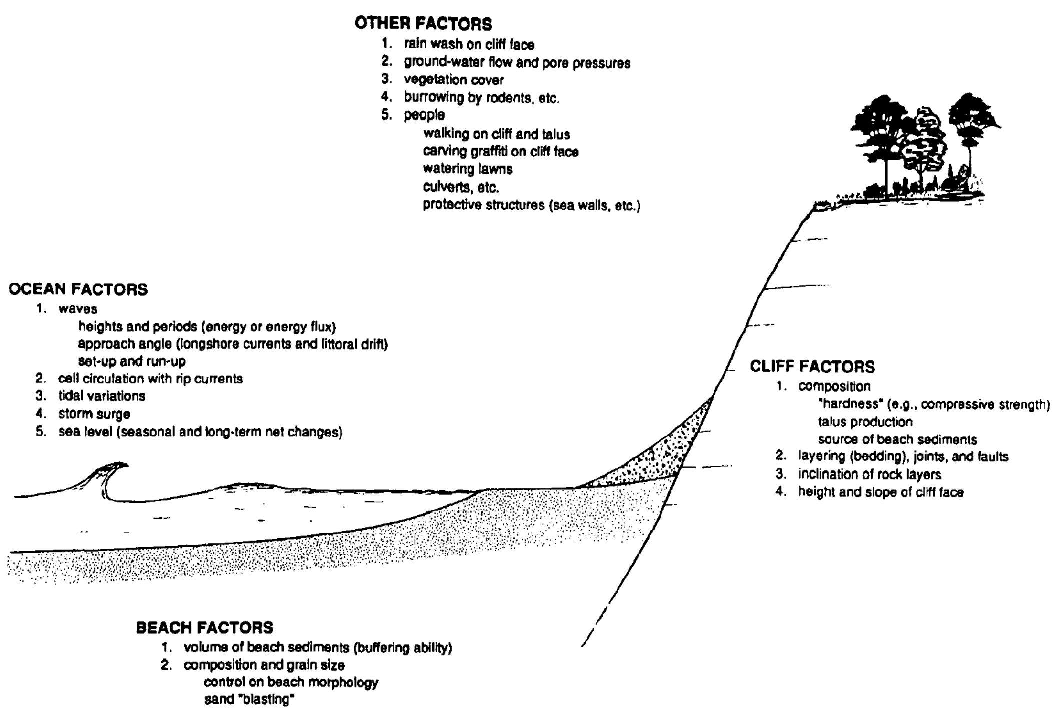


Figure 34: Schematic diagram illustrating the many factors and processes involved in sea-cliff erosion.

Only limited study has been devoted specifically to cliff erosion along the Oregon coast. The earliest work examined the occurrence of major landslides and documented the importance of factors such as rainfall intensity and rock jointing and bedding (Byrne 1963, 1964; North and Byrne 1965). Little information is available on the long-term erosion rates of sea cliffs not affected by major landslides. Stembridge (1975) compared two sequences of aerial photographs (1939 and 1971) to estimate erosion rates, but his analysis was limited to only a few areas along the coast and yielded rough estimates of long-term changes. In a more detailed study, but one limited to Lincoln County, Smith (1978) also used aerial photographs to document average cliff erosion rates. Both studies revealed a considerable degree of spatial variability along even short distances of the coast. They also recognized the episodic nature of the cliff erosion processes.

Our on-going Sea Grant research focuses on the patterns and processes of cliff erosion along the Oregon coast. This work has examined the tectonic controls on the spatial variability of cliff erosion along the full length of the coast, beach-process factors in cliff retreat within more limited stretches of shore, erosion/management issues at specific locations, and the impacts of engineering structures (Komar and McDougal 1988; Komar et al. 1991; Komar and Shih 1991; Sayre and Komar 1988; Shih, in prep.). Our research has confirmed that sea-cliff erosion is highly variable along the Oregon coast, but suggests that the patterns are systematic and depend in part on the tectonic uplift versus global sea-level rise established in figure 4. The north-central portion of the coast, including the areas of Newport and Lincoln City, are experiencing some relative sea-level rise, while further north toward Cannon Beach and south of Coos Bay the tectonic uplift has exceeded the rate of sea-level rise, at least within historic times. There is a rough first-order parallel between the extent of cliff erosion and relative sea-level changes, with greater amounts of erosion occurring in the Lincoln City area of the central coast (Komar and Shih 1991). Of particular interest is the minimal erosion within historic times of sea cliffs in the Cannon Beach and Bandon areas. What little cliff retreat exists is associated with ground-water seepage. Direct wave attack of cliffs backing the beach has been almost nonexistent, accounting for little or no erosion. Yet the steepness of the cliff and its alongshore uniformity without appreciable degradation by subaerial processes suggest that the cliff has experienced wave erosion in the not-too-distant past. This condition is more evident at Bandon on the south coast, where, in addition to the steep cliff backing the beach, a number of stacks exist in the immediate offshore, many having flat tops which continue the level of the marine terrace (Komar et al. 1991). Our interpretation of both the Cannon Beach and Bandon areas is that cliff erosion was initiated following the last major subduction earthquake 300 years ago, an event that likely resulted in the abrupt subsidence of those areas. However, the subsequent aseismic uplift has progressively diminished the cliff erosion, to the point where it has essentially ceased at Cannon Beach and Bandon. The central coast around Lincoln City likely also experienced subsidence followed by uplift, but its rates of uplift have been insufficient relative to rising sea level to halt continued cliff erosion.

Such tectonic/sea-level controls of cliff erosion along the Oregon coast can be viewed as a first-order pattern or trend. Superimposed on this coastwide variability are more local processes that can be viewed as second-order factors. Most important is the size of the beach, as this governs the ability of the beach to act as a buffer between the sea cliffs and the eroding processes of waves and nearshore currents. The width and elevation of the beaches vary from one littoral cell to another, each littoral cell consisting of a stretch of beach isolated by rocky headlands. For example, the beach extending north from Yaquina Head to Otter Rock and Cape Foulweather, the Beverly Beach littoral cell, does not offer adequate buffer protection, and as a result the sea cliffs backing this beach have undergone significant retreat (though still at low rates when compared with other coastlines). Its limited buffering capacity is evident in our ongoing measurements of wave run-up (Shih, in prep.). The objective is to document the frequency with which waves reach the talus and base of the sea cliff, and the intensity of the swash run-up when it does so.

Video-analysis techniques are being employed to record the run-up. The measurements have established that the swash of waves frequently reaches the cliff base in the Beverly Beach cell, but rarely in the other cells. Beach surveys show that this is due to the low elevations of the beach profile with respect to mean sea level and high-tide elevations.

Of particular interest in our study of sea-cliff erosion has been the littoral cell containing Lincoln City and Gleneden Beach, extending north from Government Point (Depoe Bay) to Cascade Head. The extensive development along this stretch of coast has given rise to a host of management problems (figure 33). In addition, an unusual feature, marked longshore variations in the coarseness of the beach sands, produces longshore changes in the beach morphology and nearshore processes that are important to cliff erosion. We have completed a detailed study of the changing grain-size distributions from beach-sand samples collected along the full length of this cell (Shih, in prep.). Our analyses show that the longshore variations in grain sizes are produced by the relative proportions of discrete grain-size modes within the overall sand-size distributions. We have succeeded in tracing these individual modes to specific areas of the eroding sea cliffs. Of interest are how these grain-sized modes move and mix alongshore and why the mixing processes of the nearshore have not succeeded in homogenizing the beach sands to eliminate longshore variations. However, the overall effect of this longshore sorting is that the beaches toward the central to south part of the cell are coarsest; this includes the beaches fronting Siletz Spit and the community of Gleneden Beach. Sand sizes decrease somewhat toward the south, but particularly toward the north where the sand is finest in the Roads End area of Lincoln City. The effects on the beach morphology are significant, with the coarse-grained beach at Gleneden being a steep "reflective" beach for most of the year while the beach at Roads End has a low slope and is highly "dissipative" of the waves as they cross the wide surf zone.

Beach profiles have been obtained at eleven stations spaced at roughly even intervals along the length of the Lincoln City littoral cell in order to document the beach morphologies and how they change with sediment sizes (Shih, in prep.). In addition, high-density profiling has been undertaken at approximately monthly intervals for over a year at Gleneden Beach State Park (a reflective beach) and at the 21st Street beach access at the north end of Lincoln City (a dissipative beach). This high-density profiling permits the generation of detailed topographic maps of the beach and more accurate analyses of seasonal changes. Of particular interest in this series of profiles is the contrast in responses of the reflective and dissipative beaches to winter storms. The results document that profile changes and accompanying quantities of cross-shore sediment transport are much greater on the coarse-grained reflective beach (Gleneden Beach) than on the finer-grained dissipative beach at the north end of the littoral cell. The rates of change as well as total quantities of sand moved under a given storm are larger on the steep reflective beach. This makes the reflective beach a weaker buffer from wave attack, and cliff erosion is therefore more active than in the area where the cliff is fronted by a fine-grained dissipative beach. In addition, we have found that the development of rip-current embayments is extremely important on the reflective beach. These embayments largely control the locations of maximum episodic cliff erosion (figure 35). The process is similar to that described earlier for the erosion of Siletz Spit, immediately north of Gleneden Beach, which is also fronted by a reflective beach (figure 21). Ground observations and aerial photographs show that rip currents on steep reflective beaches tend to cut narrow, deep embayments, and so they exert a significant role in controlling the impact of erosion along the sand spit and also in the the sea-cliff areas. In contrast, rip-current embayments on the dissipative beaches of north Lincoln City and elsewhere on the coast are broader in their longshore extents but do not cut as deeply through the beach berm.

Bluff retreat in north Lincoln City, where the dissipative beach is present, depends mainly on subaerial processes of rainfall against the cliff face and groundwater seepage. People have also had a significant impact; in some places their carving graffiti on the cliff face is the dominant factor in bluff retreat (figure 36). The loosened material accumulates as talus at the base of the cliff. That accumulation can continue for several years, at which time it is removed by wave action during an unusually severe storm accompanied by extreme tide levels. There is little direct wave attack of the cliff and no evidence for undercutting. However, once the talus has been removed by waves, sloughing of the cliff surface accelerates so that a new mass of talus quickly forms.

Landsliding has been a problem at some locations along the Oregon coast. This is particularly the case where Tertiary marine formations are included in the sea cliff (figure 2), since their muddy consistency makes them especially susceptible to sliding. Furthermore, it has been estimated that these units dip seaward along more than half of the northern Oregon coast (Byrne 1964; North and Byrne 1965), a geometry which also contributes to their instability. In some cases this instability results in the slow mass movement of the cliff material toward the sea, amounting to only a few 10s of centimeters a year. Although slow, it thoroughly disrupts the land mass and any attempts to place developments on the site (figure 37). Other landsliding involves the whole-scale movement of large masses at more rapid rates. Best known is the infamous Jump-Off Joe area of Newport. In 1942 a large landslide developed in the bluff, figure 38, carrying more than a dozen homes to their destruction (Sayre and Komar 1988). In spite of continued slumping, in 1982 a condominium was built on a small remnant of bluff adjacent to the major slide. Within three years, slope retreat had caused the foundation to fail (figure 39), and the unfinished structure had to be destroyed by the city.

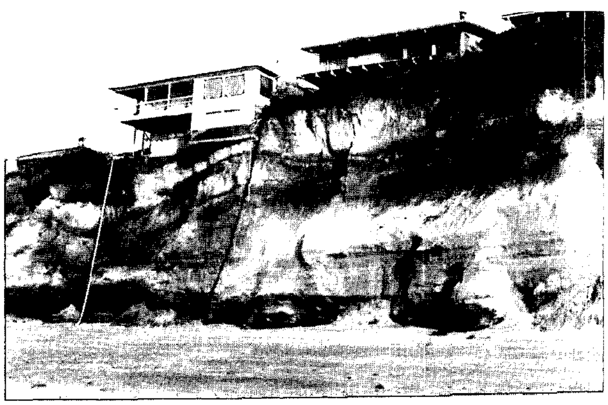


Figure 35: Cliff erosion in Gleneden Beach due to a pronounced rip-current embayment that permitted the swash of storm waves to reach the cliff base.

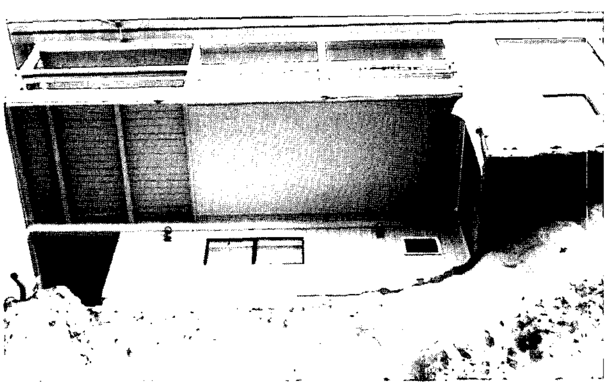


Figure 36: The retreat of the bluff in Lincoln City caused by children carving graffiti and digging caves.

Summary

The Oregon coast is renowned for the intensity of its wave conditions. Winter storms commonly generate individual waves 40 to 50 feet high. The record is 95 feet. Such storm waves deliver a tremendous amount of energy to our coast, cutting back beaches and attacking coastal properties. They are assisted by rip currents that locally erode embayments into the beach, as well as tides and other processes that elevate water levels in the nearshore. In addition to these natural processes, people have contributed to the erosion, ranging from children's carving their names on the face of sea cliffs to the Corps of Engineers' constructing a jetty at the inlet to Tillamook Bay.

The Oregon coast has had its share of erosion problems. Most dramatic has

Figure 37: The destruction of streets and sewers by landsliding within a new development north of Yaquina Head.

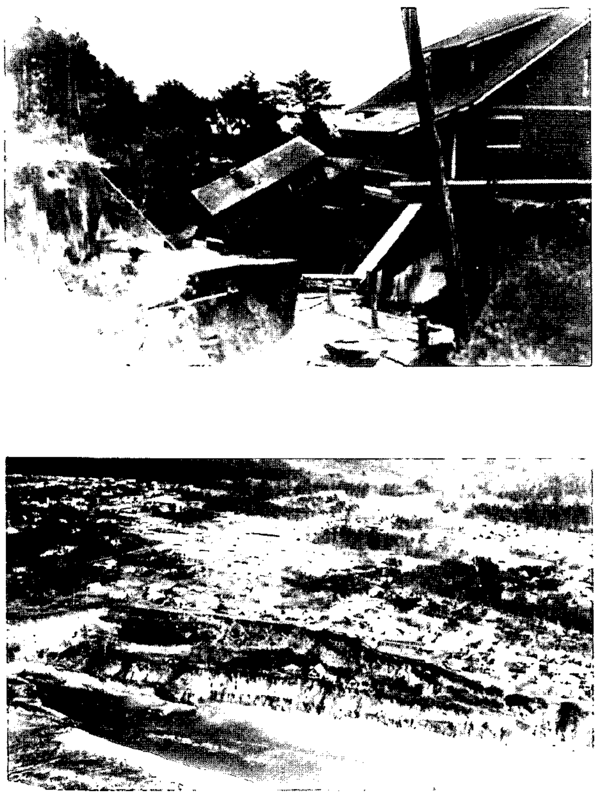


Figure 38: The 1942-43 landslide at Jump-Off Joe, Newport, showing the initial destruction of homes. The aerial photo dates from 1961. (Photos from Lincoln County Historical Society, Newport)

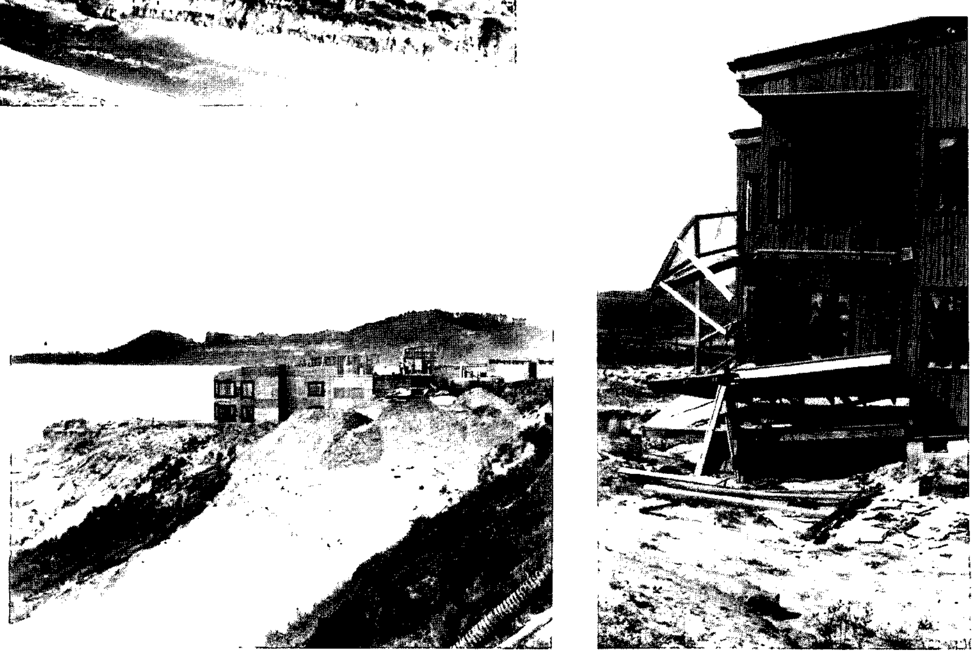


Figure 39: The construction (far left) and destruction (left) of the condominium built in 1982 on a small remnant of marine terrace at Jump-Off Joe. (From Sayre and Komar [1988])

been the impact on sand spits; several case studies have been summarized in this chapter. Though less dramatic, the cumulative erosion of sea cliffs has affected a number of coastal communities as well as parklands and highways. However, the Oregon coast has actually suffered relatively few erosional impacts leading to major property losses, at least in comparison with most other coastal states. This is in part due to its physical setting. The coast consists of a series of pocket beaches or littoral cells separated by rocky headlands or more extensive stretches of rocky shore. In each cell there is a seasonal reversal in the direction of longshore sand transport, but with a long-term net drift that is essentially zero. As a result, when jetties have been constructed on the Oregon coast, they cause only a local rearrangement of beach sands and adjustments of the shorelines, with no lasting major impacts (the one exception was Bayocean Spit, where erosion was due to the construction of one jetty rather than two). This contrasts with most U.S. shorelines, where jetty and breakwater construction has blocked a net littoral drift and severely eroded the downdrift beaches and communities.

The tectonic setting of the Oregon coast is also important in limiting its erosion. Most significant is the tectonic uplift that currently exceeds the global rise in sea level over much of the coast, while minimizing the transgression of the sea in other areas. Unlike the east and Gulf coasts of the U.S., where the transgression has resulted in substantial landward migrations of the shoreline and property losses, erosion of Oregon's sandy shores is cyclical, with minimal net loss. This was first noted on Siletz Spit, where an episode of erosion cutting into the foredunes was followed by a decade of accretion so that the dunes built back out to their former extent. An extreme example was noted on Nestucca Spit, where an extensive mound of riprap placed during erosion in 1978 is now covered by dune sands that are blowing inland, inundating houses. Similarly, the tectonic uplift has resulted in low rates of cliff recession, much smaller than those documented in other coastal areas.

This situation may change in the future. There is the potential for accelerated rates of sea-level rise caused by greenhouse warming that could exceed the tectonic rise and bring about more extensive erosion. Although the impact would be smaller and come later than it would along the low-relief and subsiding coastal states, it is important that potential increases in sea level enter into management considerations for the Oregon coast. More ominous is the possibility that an extreme earthquake will occur on the Northwest coast. In addition to the immediate impacts of the ground shaking and the generation of a tsunami, the abrupt subsidence of portions of the coast will initiate extensive erosion in areas that have not suffered from wave attack within historic times. The implications of this scenario for coastal planning are staggering, yet the decisions officials must make are not simple ones. As discussed above, it has been estimated that catastrophic earthquakes and land-level changes have occurred at least six times in the past 4,000 years, at intervals ranging from 300 to 1,000 years. The last recorded event took place about 300 years ago, so we are clearly in the window of potential for another event. At some stage, and preferably sooner than later, coastal management decisions need to be made reflecting this potentially extreme hazard. In the meantime, we have to reflect on the wisdom of developing low-lying areas and the edges of ocean cliffs along the coast.

We have made numerous mistakes in developing the Oregon coast that have placed homes and condominiums in the path of erosion. Development has been permitted in the foredunes of sand spits immediately backing the beach, along the edges of precipitous sea cliffs, and even in the area of the active Jump-Off Joe landslide. Such unwise developments and the accompanying proliferation of seawalls and riprap revetments has progressively degraded the qualities we cherish in the Oregon coast.

Acknowledgments

This review was funded by a grant from the National Oceanic and Atmospheric Administration, Office of Sea Grant (grant NA89AA-D-SG108, project R/CM-36). The views expressed are those of the author and do not necessarily reflect the views of NOAA or any of its subagencies. I would like to thank Jim Good, Kevin

Tillitson, Shuyer-Ming Shih, and Mark Lorang for their helpful comments in reviewing this paper.

References

Aguilar-Tunon, N.A., and Komar, P.D., 1978, The annual cycle of profile changes of two Oregon beaches: The Ore Bin 40:25-39.

Atwater, B.F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington state: Science 236:942-944.

Atwater, B.F., and Yamaguchi, D.K., 1991, Sudden, probably coseismic subsidence of Holocene trees and grass in coastal Washington State: Geology 9:706-709.

Boggs, S., 1969, Distribution of heavy minerals in the Sixes River, Curry County, Oregon: The Ore Bin 31:133-150.

Boggs, W.S., and Jones, C.A., 1976, Seasonal reversal of flood-tide dominated sediment transport in a small Oregon estuary: Geological Society of America Bulletin 87:419-426.

Byrne, J.V., 1963, Coastal erosion, northern Oregon: *in* Essays in Marine Geology in Honor of K.O. Emery, Univ. of Southern California Press, Los Angeles, California, p. 11-33.

Byrne, J.V., 1964, An erosional classification for the northern Oregon coast: Assoc. of American Geographers Annals 54:329-335.

Clemens, K.E., and Komar, P.D., 1988a, Oregon beach-sand compositions produced by the mixing of sediments under a transgressing sea: Journal of Sedimentary Petrology 58:519-529.

Clemens, K.E., and Komar, P.D., 1988b, Tracers of sand movement on the Oregon coast: Proceeding 21st Coastal Engr. Conf., Amer. Society Civil Engrs., p. 1338-1351.

Creech, C., 1981, Nearshore wave climatology, Yaquina Bay, Oregon (1971-1981): Oregon State Univ. Sea Grant Program, Report ORESU-T-81-002.

Darienzo, M.E., and Peterson, C.D., 1990, Episodic tectonic subsidence of late Holocene salt marshes, northern Oregon central Cascadia margin: Tectonics 9:1-22.

Enfield, D.B., and Allen, J.S., 1980, On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America: Journal of Physical Oceanography 10:557-578.

Hicks, S.D., 1972, On the classification and trends of long period sea level series: Shore and Beach 40:20-23.

Hicks, S.D., Debaugh, H.A., and Hickman, L.E., 1983, Sea level variations for the United States, 1855-1980: U.S. Dept. of Commerce, NOAA, National Ocean Service, Rockville, MD.

Huyer, A., Gilbert, W.E., and Pittock, H.L., 1983, Anomalous sea levels at Newport, Oregon, during the 1982-83 El Niño: Coastal Oceanography and Climatology News 5:37-39.

Komar, P.D., 1976, Beach Processes and Sedimentation: Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Komar, P.D., 1978, Wave conditions on the Oregon coast during the winter of 1977-1978 and the resulting erosion of Nestucca Spit: Shore and Beach 46:3-8.

Komar, P.D., 1983a, The erosion of Siletz Spit, Oregon: *in* Handbook of Coastal Processes and Erosion, CRC Press, Boca Raton, Florida, p. 65-76.

Komar, P.D., 1983b, Coastal erosion in response to the construction of jetties and breakwaters: *in* Handbook of Coastal Processes and Erosion, CRC Press, Boca Raton, Florida, p. 191-204.

Komar, P.D., 1985, Oregon: *in* The World's Coastline, E.C. Bird and M.L. Schwartz (eds.), Van Nostrand Reinhold Co., New York, p. 23-26.

Komar, P.D., 1986, The 1982-83 El Niño and erosion on the coast of Oregon: Shore and Beach 54:3-12.

Komar, P.D., and Rea, C.C., 1976, Erosion of Siletz Spit, Oregon: Shore and Beach 44: 9-15.

Komar, P.D., and Terich, T.A., 1976, Changes due to jetties at Tillamook Bay, Oregon, Proceedings 15th Coastal Engr. Conf., Amer. Soc. Civil Engrs., p. 1791-1811.

Komar, P.D., Quinn, W., Creech, C., Rea, C.C., and Lizarraga-Arciniega, J.R., 1976a, Wave conditions and beach erosion on the Oregon coast: The Ore Bin 38:103-112.

Komar, P.D., Lizarraga-Arciniega, J.R., and Terich, T.A., 1976b, Oregon coast shoreline changes due to jetties: Jour. Waterways, Harbors and Coastal Engr., Amer. Society Civil Engrs. 102(WW1):13-30.

Komar, P.D., and McKinney, B.A., 1977, The spring 1976 erosion of Siletz Spit, Oregon, with an analysis of the causative storm conditions: Shore and Beach 45:23-30.

Komar, P.D., and McDougal, W.G., 1988, Coastal erosion and engineering structures: The Oregon experience: Journal of Coastal Research 4:77-92.

Komar, P.D., Good, J.W., and Shih, S.-M., 1988, Erosion of Netarts Spit, Oregon: Continued impacts of the 1982-83 El Niño: Shore and Beach 57:11-19.

Komar, P.D., and Good, J.W., 1989, Long-term erosion impacts of the 1982-83 El Niño on the Oregon coast: Coastal Zone '89: Amer. Society Civil Engrs., p. 3785-3794.

Komar, P.D., Torstenson, R.W., and Shih, S.-M., 1991, Bandon, Oregon: Coastal development and the potential for extreme ocean hazards: Shore and Beach 59:14-22.

Komar, P.D., and Shih, S.-M., 1991, Sea-cliff erosion along the Oregon coast, Coastal Sediments '91, Amer. Society Civil Engrs., p. 1558-1570.

Kulm, L.D., and Byrne, J.V., 1966, Sedimentary response to hydrography in an Oregon estuary: Marine Geology 4:85-118.

McKinney, B.A., 1977, The Spring 1976 erosion of Siletz Spit, Oregon, with an analysis of the causative wave and tide conditions: Master of Science Thesis, Oregon State University.

Mitchell, C.E., Weldon, R.J., Vincent, P., and Pittock, H.L., 1991, Active uplift of the Pacific Northwest margin (abstract): EOS, the American Geophysical Union.

National Research Council, 1983, Changing climate: Report of the carbon dioxide assessment committee: Washington, D.C., National Academy Press.

National Research Council, 1987, Responding to changes in sea level: Engineering implications. Washington, D.C., National Academy Press.

North, W.B., and Byrne, J.V., 1965, Coastal landslides in northern Oregon: The Ore Bin 27:217-241.

Peterson, C., Scheidegger, K.F., and Komar, P.D., 1982, Sand-dispersal patterns in an active-margin estuary of the northwestern United States as indicated by sand composition, texture and bedforms: Marine Geology 50:77-96.

Peterson, C.D., Scheidegger, K.F., and Schrader, H.J. 1984a, Holocene depositional evolution of a small active-margin estuary of the northwestern United States: Marine Geology 59:51-83.

Peterson, C., Scheidegger, K.F., Komar, P.D., and Niem, W., 1984b, Sediment composition and hydrography in six high-gradient estuaries of the northwestern United States: Journal of Sedimentary Petrology 54:86-97.

Phipps, J.B., and Smith, J.M., 1978, Coastal accretion and erosion in southwest Washington: Department of Ecology, State of Washington, Olympia.

Rogers, L.C., 1966, Blue Water 2 lives up to promise: Oil and Gas Journal, Aug. 15, p. 73-75.

Sayre, W.O., and Komar, P.D., 1988, The Jump-Off Joe landslide at Newport, Oregon: History of erosion, development and destruction: Shore and Beach 52:15-22.

Shih, S.-M., in prep. Ph.D. thesis, Oregon State University, Corvallis, Oregon.

Scheidegger, K.F., Kulm, L.D., and Runge, E.J., 1971, Sediment sources and dispersal patterns of Oregon continental shelf sands: Journal of Sedimentary Petrology 41:1112-1120.

Scheidegger, K.F., and Phipps, J.P., 1976, Dispersal patterns of sand in Grays Harbor estuary, Washington: Journal of Sedimentary Petrology 46:163-166.

Smith, E.C., 1978, Determination of coastal changes in Lincoln County, Oregon, using aerial photographic interpretation: Research Paper, Dept. of Geography, Oregon State Univ., Corvallis.

Stembridge, J.E., 1975, Shoreline changes and physiographic hazards on the Oregon coast: Ph.D. dissertation, Dept. of Geography, Univ. of Oregon, Eugene.

Terich, T.A., and Komar, P.D., 1974, Bayocean Spit, Oregon: History of development and erosional destruction: Shore and Beach 42:3-10.

Vincent, P., 1989, Geodetic deformation of the Oregon Cascadia Margin: M.S. dissertation, Univ. of Oregon, Eugene.

Watts, J.S., and Faulkner, R.E., 1968, Designing a drilling rig for severe seas: Ocean Industry 3:28-37.

Wyrtki, K., 1984, The slope of sea level along the equator during the 1982/1983 El Niño: Journal of Geophysical Research 89:10,419-24.

Zopf, D.O., Creech, H.C., and Quinn, W.H., 1976, The wavemeter: A land-based system for measuring nearshore ocean waves: MTS Journal 10:19-25.

Comments on Paul Komar's "Coastal Zone Processes and Hazards"

John Beaulieu
Oregon Department of Geology and Mineral Industries

Introduction

The Oregon Department of Geology and Mineral Industries is involved in diverse activities in the Oregon coastal zone. They include participating in the Oregon Policy Advisory Commission; regulating oil, gas, and geothermal exploration and drilling from a technical standpoint; sponsoring the Exclusive Economic Zone Data Need Symposium held in the fall of 1991; and collecting routine data. In the 1970s, the department investigated geologic hazards in all coastal Oregon counties. Its investigation included some consideration of coastal processes.

As a result of these various activities, the agency has developed an admittedly incomplete, yet useful, knowledge of some of the coastal hazards that Oregonians must deal with. The topical information, field data, geological perspectives, and even personal opinions that sometimes get stirred around yield occasional insights of value to people grappling with coastal issues.

In spite of all the good work that is going on at the coast, there is a disturbing pattern that we observe from time to time. I would like to describe that pattern to you and then suggest nine possible ways it can be avoided. As I do this, I will comment on Paul Komar's paper.

It was during the 1970s that Oregon became enlightened in regard to hazards in the coastal zone. It was then that coastal studies began, the Marine Science Center was built, and state government began to put into place goals for dealing with coastal problems. In one flash of brilliance, for example, the concept of the foredune was developed. It became the cornerstone of the coastal goal. We learned that a foredune in a given location was unstable and therefore that such instability must be considered in future development.

Over the years some of us have seen these sparks of enlightenment slowly fade to dull, but everlasting, embers. They have become dogmas to be applied in all cases, regardless of specific circumstances. The questions in my mind as I read Komar's paper were, where did we go wrong, and does the paper help us find a new direction?

Nine Standards of Decision Making

When I look at coastal decision making, I apply nine standards.

1. Facts vs. Preference

When dealing with a coastal issue, are we placing facts on the table, or are we trying to rationalize a personal preference? Looking at Komar's paper, I see good factual discussions of pocket beaches, sea level trends, the seasonality of processes, currents, grain size, and so on. His paper provides the conceptual framework that can lead to factual and objective analysis of situations where decisions must be made. I don't believe I read the words "in my opinion" anywhere in the text.

2. Inventories vs. Anecdotes.

In making a policy decision that affects one area, it is easy to turn to another area that superficially seems the same and then to conclude that the first area in question should be treated the same as the second. We don't need anecdotes; we need inventories of facts to help us make decisions. The Komar paper provides us with a number of good parameters for developing such inventories. Although Komar gives examples here and there to clarify a point, he makes no argument by anecdote.

3. New Concepts vs. Personal Experience

It is common in coastal studies to hear people stretch their personal knowledge beyond its application to arrive at conclusions that may not be appropriate. We need individuals who seek out and use emerging concepts and technologies with which they are not initially familiar. In Komar's work, we see information on subduction zone earthquakes. These and other concepts are fairly new to the scene and we need to learn more about them.

4. Perspective vs. Emotion

When a problem is identified on the coast, it is very easy for us to react emotionally, not because the situation truly justifies such a response, but because we have a strong personal stake in the outcome. Facts allow us to put the problem into perspective. The Komar paper proceeds from factual discussions and provides the basis for perspective. Just one example will suffice. Quite often when we read about coastal erosion, we are told about the loss of sand and cliff but not about the rebuilding that may follow. Yet here in Oregon, where the coastline basically is held up by headlands, cycles of erosion are commonly followed by rebuilding. In such cases, focusing only on the erosion would be very misleading. Komar gives us examples of both erosion and reconstruction. This provides us with a fuller picture of the hazards we are dealing with.

5. Reasons vs. the Real Reasons

We are often given many reasons why a particular development or proposition either can or cannot proceed. The arguments may sound good to the uninitiated, but to persons well versed in the subject they ring hollow. The question is, what are the real reasons for making a decision? One key to more accurately identifying real reasons is to use a multidisciplinary approach in which various factors can be played against each other to arrive at the best conclusion. Komar addresses many of the major factors at play along the Oregon coast and therefore provides a basis for identifying real reasons for making decisions.

6. Analyses vs. Analogies

People who discuss coastal problems often do so using analogies that may or may not apply. What is needed is more factual data with which to make sound decisions. Komar gives us examples, interpretations, and discussions, which by their nature identify the types of analyses that can give us good answers. Whereas many conclusions about the coast begin with, "Everybody knows" or "I know of another beach where . . . ," Komar provides distinct conclusions and principles relating to grain size, grain composition, and other quantitative measurements. With this kind of approach, we can make better decisions.

7. No Risk vs Acceptable Risk

How much risk is acceptable to society? Looking at the east coast of North America, we see that a risk of hurricanes every 10 years or so is considered acceptable. Building continues with proper insurance and evacuation plans. Here on the West Coast we may have different standards of what is acceptable and what is not. To properly implement a coastal hazard policy, we must identify the level of acceptable risk. It may not be enough to simply say that over some time frame we may incur some kind of risk.

8. No Rules of Thumb

A strictly geographic approach is primarily descriptive and tends to clarify and categorize coastal features. Variables in the Oregon coastal zone don't allow this approach as an end in itself. Winter waves are not the same as summer waves. Sand reservoirs come and go. Migrating sand gets around some headlands but not others. What we think we see on the Oregon coast isn't necessarily what we get. No two beaches are exactly the same at any given time. Further, no beach is the same through time because now we hear, for example, that the land rises and falls with seismic events and interseismic deformation, respectively—or the opposite, depending on where you are. Or the sea rises and falls with El Niño.

9. Implementation Strategy vs. Conflict Management

Once we have collected all the facts and defined acceptable risks, we still need a strategy for implementing decisions. Looking at various examples along the Oregon coast, such as Rogue Shores, Breakers Point, and Alsea Spit, we see a little too much conflict and not enough faith in conflict resolution or decision making.

Oregon has been deficient in translating data to acceptable policies. Through hit or miss tactics, we register geologists, we discuss the format and the contents of reports, and sometimes we play with the idea of circuit riders, or experts, who can go around and help out. Other states are more focused. Oregon cities and counties need to settle upon strategies for translating data into policy decisions.

I began by saying that there were certain standards I applied to any decision making along the coastal zone. In the simplest of terms, these standards implied reliance on facts, appreciation for variability, judgments of risk, and strategies for implementation. With these standards in mind, Komar's paper should be required reading for policymakers in the Oregon coastal zone.

ENGINEERING

SHORE PROTECTION AND ENGINEERING WITH SPECIAL REFERENCE TO THE OREGON COAST

Nicholas C. Kraus
Coastal Engineering Research Center, Vicksburg, Mississippi

William G. McDougal
Department of Civil Engineering, Oregon State University

Introduction

The need for engineering solutions to problems of chronic coastal erosion was recognized nationally in 1930 when the United States Congress authorized formation of the Beach Erosion Board (BEB) and designated the U.S. Army Corps of Engineers as the Federal entity responsible for shore protection. In 1954, the BEB published Technical Report Number 4 (TR4), entitled *Shore Protection, Planning and Design* (BEB 1954), with revised editions appearing in 1957, 1961, and 1966. TR4 was a milestone publication that defined and consolidated the state of knowledge on shore protection. In 1963, Congressional action created the Coastal Engineering Research Center (CERC) to supersede the BEB, and TR4 was replaced by the more comprehensive *Shore Protection Manual (SPM),* issued by CERC in 1973 and revised in 1984 (SPM 1984). The SPM serves as the authoritative reference on shore protection and coastal sediment processes and is used as a text book and design manual around the world. Recognizing many recent scientific developments and advances in engineering practice in the area of shore protection, CERC is planning a new publication tentatively called the *Coastal Engineering Manual* (CEM) that will supersede the SPM and expand into other areas of coastal engineering. The CEM will incorporate recent advances in information processing to facilitate periodic transfer of technology to coastal engineering researchers and practitioners as advances are made in this rapidly developing field.

One of the first activities of the BEB was to investigate severe erosion that was occurring along the northern New Jersey coast and the southern shore of Long Island, New York. In the past and again in 1938 and in the mid-1950s to mid-1960s, these coasts had experienced devastating hurricanes and storms that greatly eroded beaches, inundated and breached barrier islands, and even created a major tidal inlet at Shinnecock Inlet, New York. Loss of beaches was compounded by several factors: natural depletion of coastal bluffs along the New Jersey coast; retention of sand behind seawalls and revetments that would normally be released to the littoral system by the formerly eroding coastline they protected; and stabilization of inlets with jetties that blocked longshore movement of sand. These types of erosional events have occurred many times and at many locations on the U.S. shoreline. The U.S. Geological Survey (Williams et al. 1991) estimates that most of the coastline of the lower 48 states is experiencing moderate to severe erosion. The relative magnitude and distribution of this coastal erosion is shown in figure 1, adapted from Williams et al. (1991).

Examples of erosion in the Pacific Northwest are the short epochs that occurred in the winter of 1977-1978, when four severe storms attacked the Oregon coast, one during a Spring high tide that caused breaching of Nestucca Spit (Komar 1978). Another epoch occurred in the winter of 1982-1983, when both high water levels and storm waves associated with El Niño (the [Christmas] Child) occurred. El Niño is a large-scale climatological event that periodically originates off Peru around the Christmas season. El Niño has been associated with severe erosion and large-scale longshore translation of beach sediments (Komar 1986; Komar and Good 1989; Komar, Good, and Shih 1989). All coasts experience adjustment of the shoreline through long-term, short-term, and cyclical erosion and accretion events; as a coast such as Oregon's is used more, these changes become more apparent and of concern.

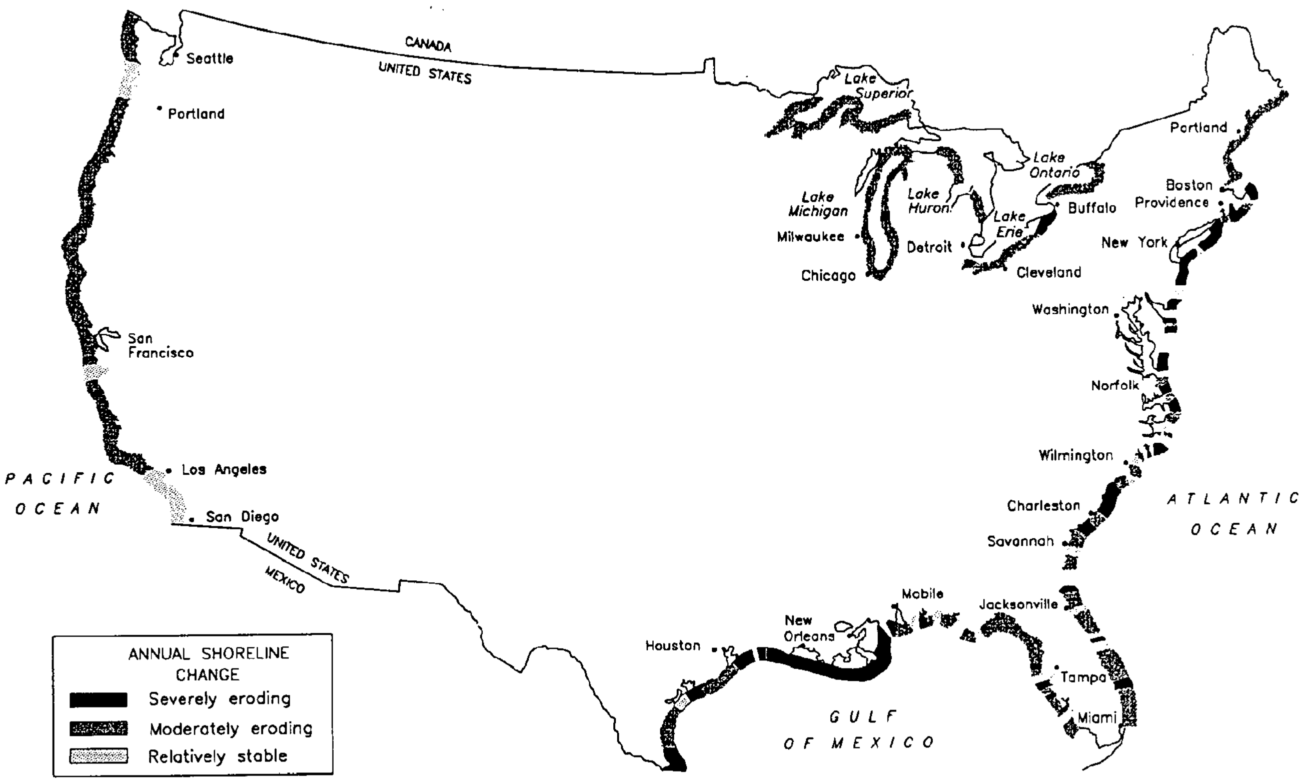


Figure 1. Coastal erosion around the continental United States (after Williams et al. 1991).

Erosion of the shore and beaches was first perceived on a regional scale in the vicinity of major coastal metropolitan areas relatively early in the century (the massive seawall built in the late 1800s along the north New Jersey coast). Erosion and inundation are now becoming concerns in other states as coastal property is developed or a desire exists to maintain natural beaches. Many states passed coastal zone management legislation in the 1970s to regulate coastal usage. These policies are typically under active debate by competing interests and undergo increasing scrutiny as both specialists and the public gain knowledge of the particular coast and better understand shore-protection measures.

Although the basic physical processes governing wave and current motion, sediment transport, and beach change are the same on all coasts, their manifestation and the relative importance of individual components can be quite different, as can be the geology and geomorphology of the coast. For example, the east coast of Florida is typified by long stretches of sandy beaches terminated by inlets, whereas the coast of Oregon is typified by relatively short pocket beaches terminated by headlands that effectively block sand from moving to adjacent compartments (for example, Komar 1991). Waves and wind, backshore and offshore topography, sediment supply, and relative sea-level rise, among other factors, also vary between coasts and, indeed, along adjacent sections of coast.

Given the preceding as backdrop, it is clear that a specific shore-protection design on one coast will probably not translate directly to another coast. Nevertheless, a body of knowledge exists on shore-protection methods. It is the intent of this paper to review these basic coastal engineering approaches and tools; they are the orthodox and generally accepted procedures for dealing with coastal erosion. In the paper, we review selected coastal sediment processes as background for the material on shore-protection methods. We then review some of the elements of shore-protection planning to establish a framework for a more specific discussion of shore-protection methods.

This paper is written from the perspective of *functional design,* a term expressing formulation and evaluation of a project by the functioning or performance of the design plan. Only occasional reference will be made to economics and construction details. Numerical simulation modeling is a useful tool in evaluating alternative designs and optimizing the final functional design. Although we do not discuss modeling in detail, we do give selected results and citations to the literature. A collection of papers on shoreline change and profile change modeling as currently performed at CERC can be found in Kraus (1990).

Elements of Shore-Protection Planning

In this section we touch on key points in the process of planning, designing, and evaluating the performance of a shore-protection project. All possible options should be available in the first stage, or *reconnaissance level,* of planning in determining possible shore-protection solutions. At the *feasibility level* of planning, which leads to the final design through intensive study and comparison of alternative plans, an *optimal plan* is developed. Here the optimal plan is taken to be the shore-protection plan that accomplishes the design objectives for the least cost and in accordance with management policies for the particular coast.

The aforementioned planning process for a shore-protection project is summarized in the following steps modified from Kraus (1989):

1. Identify the functionality requirements, identify constraints, and develop criteria for judging the performance or objectives of the project.
2. Assemble and analyze relevant data.
3. Determine project alternatives.
4. Select and optimize project design. (Return to step 1, as necessary.)
5. Construct the project.
6. Monitor and maintain the project (fine-tuning as necessary).
7. Evaluate the project according to criteria in step 1, and report the results.

The steps are more or less self-explanatory. Here, an attempt is made to encapsulize the engineering planning process in five principles.

1. Plan regionally, engineer locally

The functionality requirements and constraints (step 1) will usually encompass diverse space and time scales, requiring *comprehensive planning* as opposed to *single-project planning*. It is essential to embed the project in the regional processes of the coast, for example, over the littoral cell containing the project.

Example 1: A series of groins constructed by a group of homeowners may protect their properties but trap sand and deprive downdrift property owners. The problem statement in such a situation should include downdrift impacts, which may expand the region that should be considered, as well as the local project area.

Example 2: If a relatively undeveloped coast is experiencing a tendency for long-term erosion, such as from subsidence or loss of sand supply, it may be best to rigorously enforce set-back lines rather than attempt to hold the position of the shoreline with structures. These types of considerations typify the approach of planning regionally and engineering locally.

2. Shore retention and shore protection

Shore retention specifically refers to the maintenance of a beach, whereas shore protection in the present context means shore retention and protection of the backland. More will be said about this below. In order to maintain a beach, one must explicitly include shore-retention considerations in the shore-protection planning.

3. Compare alternatives objectively

It is wise to evaluate and compare alternative shore-protection designs for their local and regional functioning. For larger projects, numerical simulation modeling is often conducted to compare alternative designs. Each alternative is thereby evaluated in the same way. Such results are then interpreted through experience along the coast to determine the appropriate final plan. After planners evaluate the alternatives, they modify their plans; and the objective of their project may change somewhat as they learn more about the problem and its possible solutions (step 4 to step 1).

4. Be innovative

Most sites and projects have unique features that make direct transfer of solutions from one coast to another infeasible. Although solutions of a similar nature may be appropriate along the same coastline, modification of the design will probably be required to suit the local conditions. The features of projects that perform well (as determined by following steps 6 and 7) can be adopted and modified as necessary to suit conditions at the new site. In the process of evaluating alternatives, engineers may develop new or superior designs that had not previously been considered as options.

5. Fine-tune

Monitoring a project (step 6) allows us to understand its performance and maintain the required level and longevity of protection. It may be necessary to fine-tune the design, and it is common to put a project in place at minimal cost for the level of protection and build in *triggers* to signal that some action should be taken. For example, the replenishment schedule for a feeder beach (a sacrificial beach fill that is expected to erode and nourish downdrift beaches) may be initially set at the longest estimated acceptable time interval with the contingency to replenish it more frequently according to some criterion established at downdrift shores.

Physical Processes

General Processes

The success of a shore-protection design depends on understanding the driving and controlling mechanisms of sediment transport. As a means of providing background and uniformity to the discussion, we will analyze the functioning of shore-protection structures in terms of the major sediment transport processes and constraints.

It is convenient, but somewhat arbitrary, to classify sediment transport direction as being either alongshore or across-shore. *Longshore transport* denotes sediment movement parallel to the coast. On an open coast, it is mainly produced by wave breaking, which stirs and suspends the sediment and makes it available for transport by the longshore current. Waves breaking at an angle to the shoreline produce such a current. Other mechanisms producing longshore transport are barriers to waves, such as an island, jetty, or breakwater, that create a "diffraction current" by decreasing wave height and directing waves and the current into the shadow zone of the blocking object. Wind also can produce substantial longshore currents. Longshore transport is generally most intense in the surf zone, where wave breaking is active and greatly decreases in magnitude with distance seaward from the surf zone. Because longshore currents are persistent, long-term change in the beach planform is almost always related to the longshore current and associated longshore sediment transport.

Longshore transport on a coast is often described in terms of the net and gross rates of transport. An observer standing on the coast can distinguish the transport along the coast by the sand moving to the right or left, both quantities considered as being positive. The *net transport rate* is then the right-moving transport minus the left-moving transport. Some authors include the sign (if the right-moving is greater than the left-moving transport, the net is to the right and positive; if the left-moving is greater than the right-moving transport, the net is to the left and negative). Other authors define the net as the magnitude of the difference (always positive). The *gross transport rate* is the sum of the left-moving and right-moving transport and is always positive. Shoreline change due to longshore transport is controlled by the net transport, whereas the volume of sand annually entering or being trapped by a navigation channel is related to the gross transport rate (the channel accepts material from both left and right), unless sand is unequally blocked from the sides, as from jetties of unequal length.

Cross-shore transport is further classified as onshore transport and offshore transport. Important beach change phenomena associated with cross-shore transport are seasonal changes in beach width, storm-induced erosion, and post-storm recovery. Erosion by cross-shore transport is promoted by higher water levels and higher, steeper waves. Higher water levels can be produced by onshore winds, storm surge (rise in water level accompanying storms and produced by strong wind and differences in atmospheric pressure), wave-induced setup, and long-period wave motions such as surf beat, as well as by the tide.

High water levels allow waves to act on portions of the profile not preconditioned to wave action, leading to erosion. Waves will typically have greatest steepness (wave height divided by the wave length) at the peak of a storm and produce greater offshore transport (erosion); some of this material is returned onshore under the lower steepness post-storm (recovery) waves, as happens as well during the summer. Kraus, Larson, and Kriebel (1991) review the status of simple predictions of direction of cross-shore sand transport.

When waves approach the coast at a small angle, rip currents (strong and narrow currents that flow offshore) will form, and their strength depends on the height of the incident waves. Rip currents remove sand from the beach face and surf zone and carry it offshore, beyond the region of breaking waves. This material may then slowly return to the surf zone or be deposited offshore. Rips tend to form in the vicinity of structures that penetrate into the surf zone or beyond, such as groins and jetties. They also tend to appear at discontinuities in the shoreline, such as at the ends of a seawall if it projects into the surf zone (McDougal, Sturtevant, and Komar 1987) or at changes in the nearshore bathymetry such as determined by the geological structure (for example, at a transition from rocky to sandy beach). On a long, sandy coast, during days of near-normal wave incidence, rip currents tend to occur with a longshore spacing of about one to four times the width of the surf zone.

One other general concept entering our discussion of shore protection is that of the *littoral cell.* The word "littoral" refers to the active movement of sediment in the nearshore zone. A regional unit where the littoral zone is bounded laterally (along the coast) is called a littoral cell. Boundaries of littoral cells are commonly large headlands and jetties, inlets, and bays. Sometimes a littoral cell can be divided into smaller units called subcells. Typically, subcells are bounded by small headlands or changes in shoreline orientation that reduce, but do not completely stop, longshore movement of sediment.

Major sediment transport processes and constraints that can control the transport are (1) waves, (2) wind, (3) currents, (4) water level, (5) water runoff and water table (concerning cliff erosion), (6) sediment supply, (7) geomorphic controls (such as inlets and headlands), (8) geologic controls, and (9) engineering controls (structures). An example of a geologic control on sediment transport is an effectively nonerodible rocky headland that might prevent sediment movement past it. The corresponding engineering control is a long jetty.

Beach response to a shore-protection project extended into the surf zone may be expressed qualitatively as

Beach Response = F (wave and water level parameters; sediment, geologic, and geomorphic parameters; engineering activities) (1)

where *F* means "a function of" and the phrase *engineering activities* refers to actual structure (groin, breakwater, jetty), beach nourishment, and similar works. In most cases, the planner or engineer can control only parameters related to engineering activities, but as much information as possible must be gathered about the first two groups of parameters on both the local and regional level to determine the optimal engineering design.

Oregon Coast

The Oregon coast is a high-wave energy coast, and it is remarkable that it exhibits only moderate beach erosion over most of its reach, the exceptions occurring mainly at spits. As an example, according to wave hindcasts performed by CERC's Wave Information Study (WIS) group (Jensen, Hubertz, and Paine 1989), at one WIS station off Yaquina Head, in water 33 feet deep, the average significant wave height for the 20-year hindcast period 1956-1975 was 9 feet, the highest significant wave was 24 feet, and the average period of the most energetic waves was 11.2 seconds. (Significant wave height is the average height of the highest one-third of the waves in a wave observation.) The occurrence of large waves at Newport is also supported by measurements made at the Oregon State University Marine Science Center. In contrast, representative average annual wave height and period on the mid-Atlantic coast are 3 feet and 8 seconds.

Clemens and Komar (1988) provide an explanation for the stability of Oregon beaches by the complete blockage of longshore movement of sediment by headlands. Much of the Oregon coast is formed of pocket beaches that can be considered individual littoral cells with little or no exchange of sediment between cells. Seasonal shifts in wave direction move sediments alongshore in an up- and down-coast motion with a potentially high gross transport rate, but the net longshore drift is close to zero. The implication of this physical situation is that a shore-protection or navigation structure that may intercept longshore transport would cause the least disturbance if it is close to a headland terminus of the littoral cell. In contrast, such a structure located in the middle of the cell would cause maximum disturbance by interception of material from either the left or right that moves over a substantial portion of the total cell.

It is also interesting that most of Oregon's sandy beaches consist of fine-to-medium sand. Beaches on high-energy coasts usually consist of coarser sand than those on moderate or low-wave energy coasts. Yet the grain size on Oregon beaches is in the range of 0.2 to 0.3 mm, similar to that on the east coast of the United States. The explanation probably lies in *sediment supply*, since the sands available to the Oregon coast are fine-to-medium grained.

Rip currents on the Pacific coast can be very strong and have the potential to transport large amounts of sand from nearshore to the offshore, causing local erosion or an embayment. This phenomenon has been documented by, for example, Komar and Rae (1976) (Siletz Spit) and Komar, Good, and Shih (1989) (Netarts Spit). Sand spits, formed by sediments that move alongshore from the coast of the mainland, are typically low lying, and embayments carved out by rip currents that tend to persist at certain locations on these spits weaken the already fragile system.

Finally, bluffs and cliffs are major features along the coast of Oregon, and they are often developed for residential areas and recreational commercial property such as hotels, restaurants, and condominiums. Komar and Shih (1991) provide an up-to-date and authoritative description of sea-cliff erosion along the Oregon coast (see Sunamura, 1984, for more general discussion of the physical processes of cliff erosion). Sea-cliff composition is an example of the importance of the geologic setting of a site. Tectonic settling, cliff composition, presence or absence of a protective fronting beach to inhibit wave action, frequency of storm occurrence, disposition of rainwater runoff, and presence of rip currents are among the factors controlling cliff erosion. Properly engineered shoreline stabilization structures can provide cliff toe protection. However, enclosure of cliff sediments by seawalls and rubble-mound barriers blocks material that would naturally erode, enter the littoral system, and contribute to the volume of the adjacent beaches. Typically only a small percentage of a cliff's volume is beach-quality material. Fine particles originating from cliff erosion will move offshore and out of the littoral system, and large rocks will remain in place. Water runoff from the top of a cliff is a geotechnical engineering problem that can induce upper cliff failure by creating channels and washing away material to gradually produce structural defects. Water also increases the weight of the soil and usually decreases its strength. Parking lot and street runoff, as well as runoff from house roof tops and similar large volumes of controllable drainage water, should be directed around or through cliffs so as not to cause erosion or slope failures.

Shore-Protection Measures

To begin, we note that there are only four general shore-protection responses to coastal erosion:

1. Relocation
2. Nourishment
3. Stabilization structures
4. Combinations of elements of the above

These responses, of which the first three are ordered from the most passive to the most active in terms of hardening of the coast with structures, are discussed individually below. In any case, shore-protection responses are an integral component in the overall *sand management policy* for the coast and should not be implemented in isolation.

The phrase "shore protection" is a generic term that can refer to either *beach stabilization* or *backshore protection,* or to both. Beach stabilization can mean maintenance of a beach, that is, promoting the existence of a beach (shore retention), or it can mean shoreline stabilization, which implies fixing the position of the shoreline without specific regard to the condition of the beach. Backshore protection refers to protection of life and backland property from waves, flooding, and erosion. A particular shore-protection response will probably not serve all functions, and so in selecting the response or combination of responses, it is vital that one be aware of the advantages and disadvantages of the response as beach stabilization and backshore protection.

Shore protection includes the concept of *life cycle,* that is, a shore-protection structure has a certain service life. Typically, structures such as roads, bridges, and buildings have a design life of about 50 years, and it is part of the project plan to maintain the structure over its expected life through periodic inspection and repairs. Many lay persons believe that coastal engineering activities (for example, structures, beach nourishment) are in some sense permanent. This is not the case. For example, coastal structures are built to withstand a certain average condition without notable degradation and to survive the oceanic environment up to a certain extreme condition called the *design* condition. However, routine inspection and maintenance of coastal structures are required. The design condition may be the 50-year storm (wave and water level conditions which occur on the average of once every 50 years). A structure may be damaged or fail if the design condition is exceeded (arrival of the 100-year storm or arrival of two 50-year storms in the same year), and extensive repairs may be required.

The concept of a life cycle for structures is important, but difficult to quantify on the coast, where oceanic and meteorological conditions, and hence erosion, are highly variable and not fully predictable. Beach change can have a long-term contribution, for example, gradual erosion owing to loss of updrift sediment supply, and an episodic short-term contribution (storm-induced erosion). The formulation of design condition is based on risk to human life and the value of the resources protected or developed, and an effort must be made to account for both short- and long-term factors that may influence coastal evolution. For example, in the Netherlands, sea dikes and coastal dunes were designed to withstand the one in 100,000-year conditions. This level of protection is justified when entire cities lie behind the coastal defenses but is absurd for designing a beach fill to protect a parking lot on a recreational beach. Erosion is often episodic and beaches do usually fully recover, and the design life of a beach fill may be only five years, with replenishment to be considered on an as-need basis (fine-tuning). In summary, the level of protection and life cycle must suit project needs, and monitoring and maintenance schedules are important elements of an overall plan.

Relocation

Relocation is moving existing resources, such as residences, commercial buildings, and roads, landward to maintain a certain minimum distance between the resource and the location of the eroding coastline. The response of relocation is sometimes called "retreat," an emotional synonym with the nuance of limited planning and preparation. As a planning concept and tool, relocation implies that permanent structures must be built beyond some predetermined line.

Set-back lines can be defined for both sandy beaches and cliffs, and relocation may be formalized by a management policy that establishes such a line along the coast. The set-back line may be referenced to an erosion rate or to an inundation level (surge elevation associated with a storm of certain frequency of occurrence), or a combination. A requirement for new construction to be landward of the present shoreline position plus a distance that will be reached in, say, 30 years, as determined by the local long-term recession rate, is consistent with the concept of a human generation of 30 years or a structure life of about 50 years.

The State of Florida legislated a set-back line in 1970 as an interim measure while a study was underway to establish what is now called in Florida a "coastal construction control line" (CCCL). The objective was to determine the

CCCL based on sound technical criteria that had to be developed for the purpose. The CCCL defines a zone of jurisdiction for the impact of the 100-year hurricane and is determined, in part, by numerical modeling of storm-induced beach erosion and the required wave and water levels. The CCCL is applied on a county-by-county basis to take into account differences in regional trends. (Note that the Florida Division of Natural Resources restricts its jurisdiction to sandy beaches and bluffs and does not include Federal land, harbor complexes, and other developed coastal areas.) Construction seaward of the CCCL requires a permit, and no new residence is allowed within the 30-year, long-term erosion limit. In principle, the 30-year limit is to be computed each time a permit is issued to take into account most recent monitoring data and calculation procedures.

Typically, one must design a shore-protection structure, say a seawall, to withstand a 50-year or 100-year hurricane. In an interesting twist of the conventional concept, present coastal zone regulations in Florida may now be replaced by the requirement that such a structure withstand only a minor storm (perhaps a 5- or 10-year storm) and *fail* for a larger storm. The idea is that the natural force of a major storm or hurricane should be allowed to reshape the coast uniformly. For example, if a property on the coast is protected by a well-engineered seawall and survives the 100-year event while adjacent beaches erode, the wall might become a littoral barrier interrupting continuity of the beach both for humans and sediment transport. Eventually, such a barrier would probably be abandoned by the property owner if it became stranded in the surf zone.

Relocation can be promoted in erosion-prone areas by zoning coastal lots to be of sufficient landward length to allow relocation over one or two anticipated life cycles. This policy is a kind of preventive medicine that a priori recognizes the potential for that coast to erode. Where practicable (recognizing that economics, politics, and nature, among other factors, define what is practicable), relocation is becoming the preferred erosion solution on lightly developed coasts. For the public and for the property owner, relocation preserves the natural state of the coast and allows access to it. From the regional perspective, eroded sediment contributes to the littoral system, thereby helping to retard erosion elsewhere. In principle, almost any structure can be relocated. If the cost is prohibitive, however, or if the cultural value of the resource (an old fort, a lighthouse, and so on) is attached to its location, other shore-protection measures might be considered.

Nourishment

Nourishment is the only form of shore protection that will maintain a shoreline that appears natural. The Federal Government has traditionally nourished beaches for storm and hurricane protection, but not solely for recreational benefit. The fill material may be emplaced by trucking from an upland source; by pumping through a pipeline from an inlet, navigation channel, or back bay; or by dredging offshore and pumping the sediment onshore. Bypassing at inlets or any littoral discontinuity in the shoreline (see the review by Richardson [1991]) is a way of controlling placement of sand on the beach and can be done according to a predetermined schedule, for example as a function of the amount impounded at the updrift jetty of a channel. Clausner et al. (1991) describe the functioning of a bypassing plant at Indian River, Delaware, that exceeded the project goal of bypassing 100,000 cubic yards per year across the inlet. The bypassing rate is being managed to balance the need for a recreational beach on the updrift (south) beach at the inlet and beach nourishment needs on the receding downdrift (north) side of the inlet. Sand can also be "backpassed," that is, returned updrift from a downdrift impoundment area, and recycled into the littoral system. Such a solution may be appropriate for a spit receding because of longshore transport or the alongshore migration of a barrier island.

As with any construction project, the significant mobilization expense associated with nourishment makes it cost effective to place the maximum volume of material possible in a single operation. There are physical reasons for placing a substantial fill as well. If other factors (waves, thickness of fill) are equal, the longevity of a fill is proportional to the square of its length (Dean 1984; Larson, Hanson, and Kraus 1987). Benefits of a fill extend past its original lateral boundaries as the fill spreads (figure 2). Dean (1984) suggests the formation of "erosion control districts" through which several communities cooperate in placing fill over several miles. Ideally, the project should extend over a littoral cell or subcell.

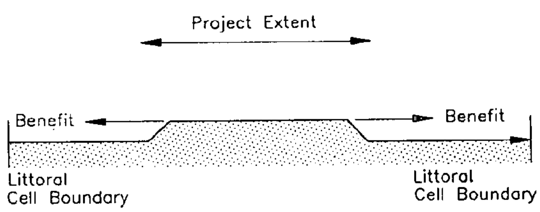


Figure 2. Plan view of a beach nourishment project.

It is possible to create a littoral subcell at a nourishment project by enclosing the fill in groins. These *terminal groins*, which function as short headlands, slow and reduce longshore spreading of the fill. In a situation where the eroding beach is downdrift of a littoral barrier such as a jetty or large inlet, a groin field (series of groins) may be placed with the fill. Groins are discussed below.

Beach nourishment material should be similar to the native sediment in the littoral system. If it is finer, the fill will tend to move offshore; if it is coarser, the beach profile will resist erosion and remain in place longer than the native material. In any case, as shown in figure 3, the profile of a nourished beach will adjust from the constructed shape to a natural equilibrium shape according to the incident waves and sediment grain size. Dean (1991) provides a review of concepts of equilibrium beach profiles. The public may perceive the apparent diminishing of the visible portion of a beach fill as a "loss." This may not be the case if the fill is simply moving out on the profile to achieve an equilibrium shape. The response of a beach nourishment project to both typical and storm waves has become an active area of research. Numerical simulation models are being developed as design tools for estimating project performance. Larson and Kraus (1991) review the status of both longshore and cross-shore modeling of beach fill. One goal is prediction of the initial adjustment of the fill to the design profile, but the major objective is evaluation of potential catastrophic dune erosion and inundation (Kraus and Larson 1988; Larson and Kraus 1989a, 1989b).

Beach nourishment can be used to construct or maintain a recreational beach, protect hard coastal structures such as seawalls, provide an erosion buffer for the backshore, and protect the backland from storm inundation. In the latter case, nourishment can be used for *dune building*—placement of sand on the beach as a foredune and then promoting its growth through the placement of sand fences to capture wind-blown sand (see Hotta, Kraus, and Horikawa 1987, 1991 for reviews) and planting of vegetation (Corps of Engineers 1972; SPM 1984). On a chronically eroding coast, dunes must be allowed to migrate landward by wind-blown sand or they will be undercut like cliffs and erode.

The cost of a nourishment project is closely related to the distance to the borrow source for beach-quality material. Coarser material is expected to last longer, and this consideration is balanced by haul distance. Often the source is obvious, such as littoral material that has shoaled into a navigation channel and is removed as part of maintenance dredging. If this dredging is performed by the Corps of Engineers, then any increase in cost incurred by placement of the material on the beach beyond the least-cost handling procedure (the least-cost restriction mandated by Congress) must be borne by the local sponsor.

Finally, a recent development in beach nourishment practice is renewed interest and research in shallow-water placement of beach-quality dredged material (see McLellan [1990] for a review and engineering details). In this procedure, which may be much less expensive than

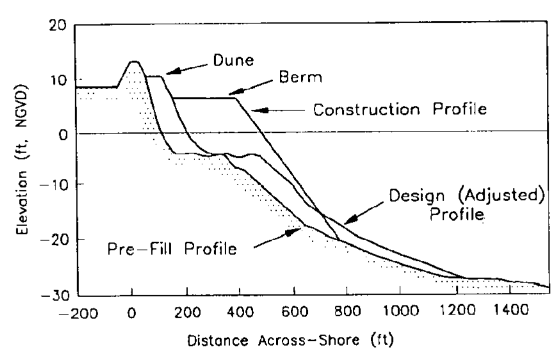


Figure 3. Adjustment of a fill to the design profile.

direct placement on the beach, dredged material is deposited in shallow water (typically, by split-hull barges), in the form of a long linear ridge that is like a naturally occurring longshore sand bar. Benefits may be direct (when the material moves onto the beach) or indirect (when the material causes storm waves to break farther offshore). McLellan and Kraus (1991) describe preliminary design criteria for shallow-water material placement.

Stabilization Structures

There are a variety of structural alternatives for stabilizing shorelines. These are often referred to as hard structures. Hard structures establish a fixed or approximately fixed position for the shoreline defense. The position of the natural shoreline is dynamic. It can change with storms and season and have a general trend over long periods. Placing permanent structures such as houses, hotels, roads, and bridges on the beach conflicts with the dynamic response of the shoreline. A structure that establishes a fixed line of defense must have sufficient structural integrity to withstand large waves, hence the term "hard structure." A soft structure, such as a beach fill, is much more compliant. It will experience large displacements and possibly major erosion during a design event.

In this section we review the functional behavior of several types of hard structures commonly used to provide shore protection (see also Dean [1986]). These are, in order of coverage, revetments, seawalls, groins, detached breakwaters, floating breakwaters, and combination structures, typically with beach fill. We consider fully engineered structures, and not low-cost shore-protection measures (Corps of Engineers 1980) that are not expected to have a long life cycle.

Revetments

Riprap revetments are the most common hard structure employed for shoreline stabilization on the Oregon coast. A typical revetment is shown in figure 4. It consists of several key components: filter fabric or bedding layer, armor stones, toe trench, sand topping, beach grass, and backshore drainage. The most conspicuous component is the armor layer that is constructed from large stones. A variety of concrete armor units are available as alternatives to stone. These units are employed in very large wave conditions or in situations where stone of sufficient size or quality is not available. The availability of stone generally makes it the cost-effective alternative for typical revetments in Oregon.

Care must be exercised in the selection and placement of armor stones. The stone must be durable and free from cracks, and materials that weather, abrade, chemically degrade, and so on, should be avoided. Rounded stones, such as river boulders, stones with one very short axis, and stones with one very long axis, should also be avoided. These shapes correspond to spheres, plates, and rods; unless very special placement techniques are employed, these odd-shaped stones will result in low levels of stability. The SPM (1984) provides guidelines for the specification of armor stone. Armor stones should be placed, not dumped. If stones are dumped on a slope, they will segregate by size with the larger stones being at the toe. Standard practice is to nest the armor stones in a layer two stones thick.

In the U.S., the required size of armor stone is determined using Hudson's equation (SPM 1984). If the revetment is built with angular quarry stones at a slope of 1V:1.5H, then the required stone weight is approximately

$$W = 16^{d\,3(2)}$$

in which W is the weight in pounds and d is the water depth at the revetment toe in feet. The depth is for the high-water storm condition and must include storm surge, astronomical tide, and

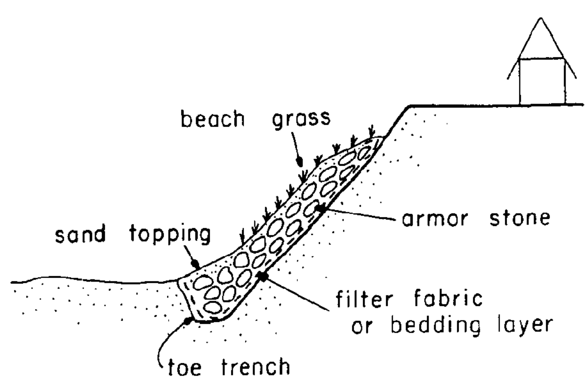


Figure 4. Schematic of a typical revetment.

scour. This simplified equation is valid only for structures shoreward of the wave breaker line (the typical situation in Oregon). If the total design depth is 3 feet, a stone weight of approximately 430 pounds would be stable. If the depth is 6 or 10 feet, the resulting weights are approximately 3,500 and 16,000 pounds. This simple example clearly demonstrates the importance of water depth on design and stability of the structure. The higher the revetment can be placed on the beach profile, the more stable it will be for a given stone size because it is not attacked by large waves.

The filter fabric, or bedding layer, performs two functions. It prevents the armor stones from sinking into the sand, and the permeability of this underlayer allows pore-water pressure beneath the revetment to be released. If a fabric is used, it should have a pore size that will contain the underlying beach sand, have a high permeability, not degrade in ultraviolet light, and have sufficient puncture strength not to be damaged by the armor stones.

The toe trench is an essential component of the revetment. Under storm wave conditions, much of the sand fronting the structure may be removed. Without a toe trench the revetment would be undermined and collapse. A rule of thumb for the depth of the toe trench is that it be excavated either down to bed rock or to the water table. When either of these conditions is encountered, the costs associated with continued excavation are prohibitive for most small revetments.

Topping the structure with sand and planting beach grass almost eliminate adverse visual impacts. Most of the time the revetment will appear as a steep slope vegetated with beach grass. Under storm conditions, sand and grass on the lower structure will erode, exposing the armor. Details regarding planting and care of beach grass are given in Corps of Engineers (1972).

Seawalls

The terms seawall, bulkhead, and retaining wall are often used interchangeably. To be more precise, a seawall provides stability against waves, a retaining wall provides geotechnical stability for a slope, and a bulkhead provides both functions. We will use the term seawall as it is commonly used in Oregon to encompass all of these cases. There are several circumstances under which the selection of a seawall may be the appropriate structural alternative: (1) There is insufficient space between the zone line and structures on the property to install a sloped revetment. (2) The bluffs behind the seawalls are unstable and susceptible to slope failure or landslides. (3) The developer wants to extend the lot seaward by filling behind the seawall.

Seawalls may be built in several ways, generally as cantilevered structures (sheet piling) or gravity structures (concrete seawall). Several types of structures are shown in figure 5. The pile-type seawall may be constructed using timber, concrete, or steel. For the timber case, piles are driven and planks are placed across the piles. Concrete or steel H-piles may be used with concrete panels or timber placed in the slots within piles. Conventional steel sheet piling may also be used. Tie-backs may be used to reduce the bending moment in the piles. Gravity seawalls may be

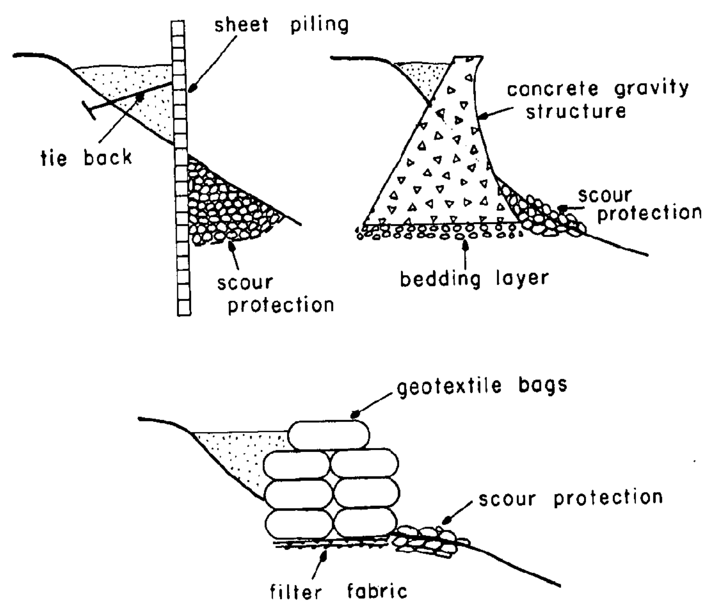


Figure 5. Examples of seawalls.

built that have a large cross-section and maintain stability through their self-weight. Gravity structures reduce or eliminate the need for driving piles. However, the material requirements are much more substantial. Gravity structures may be constructed from concrete or geotextile bags filled with sand or gravel and stacked to form the structure. Bag and tube seawalls have been successfully employed but are susceptible to damage from drifting logs (a common problem in the Pacific Northwest) and vandalism.

Wave forces acting on a seawall can be substantial. When a wave strikes the wall, large flows are directed both up and over the structure, and down toward the bottom. The upward flow may result in undesired spray and even green water over the top of the structure. For this reason, some seawalls are slightly curved seaward to direct the upwash away from the shore. At the toe, the structure is exposed to large hydraulic forces, often making it necessary to place rubble to prevent erosion or a scour pit. Toe scour is a common mode of failure for seawalls.

Seawalls can provide a high level of protection for the property backing the structure. However, a seawall provides no protection for the beach, and the location of a seawall relative to the shoreline is an important parameter (Weggel 1988). Seawalls and revetments may have several adverse impacts on the littoral system. An overview of the effects of seawalls on beaches is given in Kraus (1987, 1988), and an edited collection of papers on this topic is contained in Kraus and Pilkey (1988). The universal effect is that sand impounded behind the structure cannot participate in bar development during storms. The formation during storms of a large breakpoint bar (built from material from the upper profile) is the usual storm response of the beach. In front of a seawall or revetment, sand to develop a bar may come from unprotected properties adjacent to the structure. Therefore, the structure may increase erosion on adjacent properties, as shown in figure 6. This has been observed in the laboratory and after hurricanes on the Gulf coast (Walton and Sensabaugh 1978; McDougal et al. 1987). However, a five-year program currently underway monitoring revetments and seawalls in Oregon does not support this observation. The Oregon coast has many areas with high, weakly cemented bluffs that are often oversteepened by wave-induced erosion at the toe. The bluff face then sluffs or is winnowed away by wind and rain. A seawall or revetment reduces or eliminates toe erosion and also reduces winnowing of the bluff face. Some of this benefit extends to the adjacent unprotected properties. Preliminary field results suggest that this stabilizing effect is more important than the demand for sand for bar development during storms. Griggs et al. (1991) discuss the results of a four-year seawall monitoring program along a pocket beach in southern California. Komar and McDougal (1988) describe observations of seawall and beach interaction on the Oregon coast.

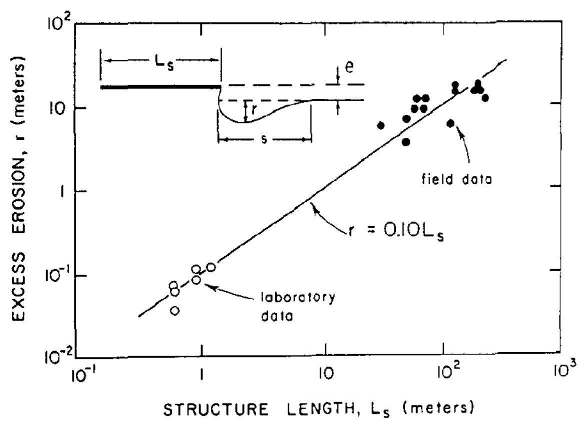


Figure 6. Erosion adjacent to a seawall.

A natural location for beach access trails is at the end of seawalls and revetments. In these areas, beach grass is destroyed and the dune and upper beach profile elevations are reduced. This weakened location will be more susceptible to erosion during storms. Since the ends of structures are already a vulnerable location, beach trails should not be developed in these areas.

Groins

A groin is a thin, long structure oriented normal or nearly normal to the shoreline. In some areas of the U.S., groins are colloquially referred to as "jetties" by the lay person, but this usage is not correct; a jetty is a structure built normal or nearly normal to the shoreline at an inlet to provide wave, current, and sediment transport reduction for vessel navigation. Therefore, jetties are located exclusively next to entrance channels, and their primary purpose is navigation-related and not shore protection. A straight groin is the simplest and most common kind. Various lateral appendages can be included to form T-shaped groins, spur groins, and so on (SPM 1984). Such appendages shadow a portion of the shoreline from direct wave action, acting like a breakwater. They may also reduce offshore loss of sediment carried by the seaward flow of rip currents near shore-normal structures. Here we restrict discussion to straight groins aligned normal to the shoreline.

A summary on the functioning of groins and the response of the shoreline to them is contained in the SPM (1984), with a useful compilation of information given in Balsille and Berg (1972). Although a groin appears to be a simple structure, the interaction of the driving forces (waves and currents) with the beach and groin is surprisingly complex. At present, available guidance on groin functioning is empirically based and must be employed with caution. Research at CERC has recently been initiated to use numerical modeling of shoreline changes (Hanson and Kraus 1989; Gravens and Kraus 1989; Hanson and Kraus 1991b) to develop more widely applicable and reliable design guidance. This work is being verified with field data. As an example, in the CERC modeling investigation, 20 variables have been identified as being in the schematic equation (1) relating beach response to forcing, beach, and structure groups of variables.

A groin performs its protective function by extending into the surf zone to intercept a portion of the longshore sand transport. Intercepted or trapped sand is no longer available to downdrift beaches. Therefore, as shown in figure 7, if the predominant direction of transport is to the left, a fillet will form on the right side of the groin, and erosion will occur on the left, with the "shoreline signature" being approximately an inverted version of the signature of the fillet (a slight difference may occur due to wave diffraction and rip currents, neglected here for simplicity). Typically, the beach slope along the accreted area will be milder than along the original beach, whereas along the eroded section the beach slope will be steeper. On the updrift side of a groin, the longshore current must be turned offshore and probably carries some sediment with it. Also, a rip current may form at the groin.

Groins are relatively ineffectual if there is a strong component of cross-shore transport, such as on the Great Lakes. There, frequent summer and winter squalls and the recovery waves that follow readily move sediment across the profile. Once offshore and beyond the tips of groins, the sediment can move alongshore.

The offshore and longshore extent of the fillet (and, conversely, the landward and longshore extent of the downdrift eroded area) will depend on the length of the groin. It logically follows that the longer the groin, the greater the extent of the accreted and eroded areas. In principle, sediment can move alongshore and past a groin in four ways: (1) passing around it on the seaward end (bypassing), (2) passing over it, (3) passing through it, and (4) passing behind it. The latter situation of sediment passing behind a groin means the groin has been flanked and is undesirable because the groin can become isolated. Therefore, groins must be built far enough landward to prevent this occurrence.

Movement of sediment over a groin is controlled by its crest elevation relative to the water level and depends on the groin elevation, tide level, and wave height and direction. Movement through the groin depends on the groin's permeability (amount of void space that allows water and sediment through). Well-engineered, impermeable groins usually have an elevation that decreases with distance offshore to allow overtopping of water and sediment as a way of

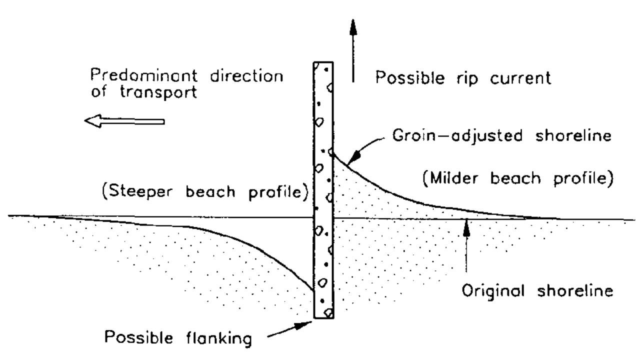


Figure 7. Schematic of beach plan form at a groin.

allowing some sediment to move alongshore. Groins constructed by the Corps of Engineers typically are rubble-mound structures with an impermeable core and have a relatively long design life.

Durable king-pile groins have been constructed consisting of concrete pilings into which planks can be stacked from the sea bed upward, with the elevation controlled by the number of planks. In principle, the amount of material passing over and through such a groin can be controlled. In practice, however, adjustment and replacement of the planks is not easy. Nevertheless, on a city or state level, the use of devices that have a fine-tuning mechanism incorporated in their design is recommended. Such structures are limited to relatively low-wave energy environments in which construction equipment can operate. Groins have also been constructed using timber, steel, and concrete sheet piling and sand-filled coffer dams.

An interesting political and legal question that has arisen with adjustable structures is, who is responsible for adjusting the groins? It is a problem because of all the associated economics, permitting, and legal consequences that would result should updrift or downdrift shorelines erode. This type of problem is a challenge to coastal management policy.

Groins are typically built in "fields," meaning two or more groins in series. Groin fields might be particularly appropriate downdrift of long jetties or headlands that intercept the longshore movement of sediment. The objective is to protect the beach in the compartments between the groins and mitigate impacts on the adjacent beaches. Figure 8 shows long groins off Newport, California, holding a protective beach for the coastal highway, and figure 9 shows a part of the groin field at Long Beach, Long Island, New York. It is standard practice to place a beach fill in groin compartments, and possibly a feeder beach so that the groin field will not entrap sand moving along the coast. However, some accumulation updrift of the groin field can be expected. The conceptual solution, shown in figure 10, is to taper the groins with gradual reduction in effective groin length towards the ends of the field. "Effective groin length" means the length in the

Figure 8. Groins at Newport, California. North is to the right in this figure. (Courtesy of A. Shak, U.S. Army Engineer District, Los Angeles.)

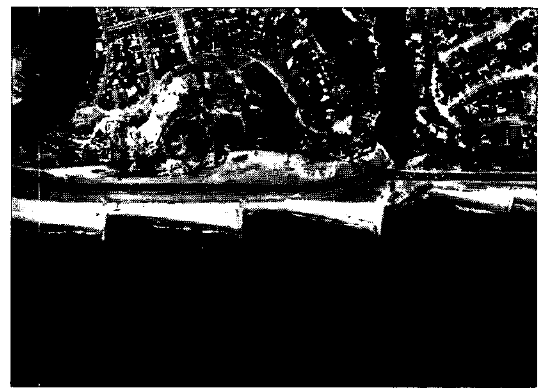


Figure 9. Groins at Long Beach, Long Island, New York. East is to the right in this figure. (Courtesy of G. Nersesian, U.S. Army Engineer District, New York.)

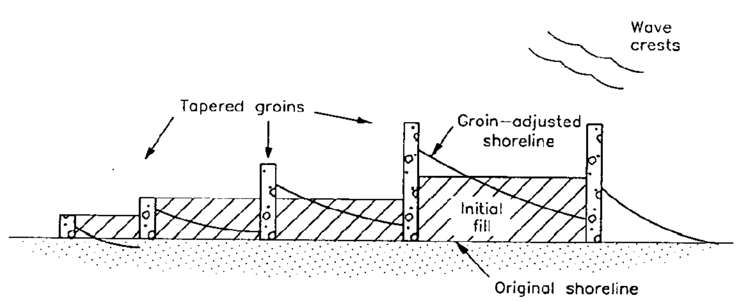


Figure 10. Schematic of tapered groins.

active surf zone. If there is substantial net transport to the left and right, the tapering should be done on both ends of the groin field.

The two questions asked early in the process of functional design of groin fields are (1) how long should the groins be? and (2) what should the spacing between groins be? These are central questions to be answered by numerical modeling now underway at CERC. For the present, the conventional answers are that the effective groin length should be approximately 40 to 60 percent of the width of the average surf zone, and the spacing between groins should be about four times the effective length. Numerical modeling results are expected to refine this simple guidance by incorporating other major factors appearing in equation 1.

As previously mentioned, it is recommended practice to fill groin compartments during construction; the filling starts at the most downdrift end of the beach segment to be protected and proceeds in the updrift direction that is occurring during the period of construction. (Note: the updrift direction depends on the wave direction during the season of construction and is not necessarily the predominant direction of drift, which is an annual average.) Also, a feeder beach may be placed at the downdrift end of the field to provide material to the adjacent, nongroined beach until the shoreline position comes into dynamic equilibrium with the groin field.

Detached Breakwaters

Detached breakwaters are structures that are built offshore and are almost always aligned parallel to the trend of the local shoreline. Detached breakwaters are sometimes referred to as "offshore breakwaters." Because most coastal structures are, in some sense, located offshore, this expression is somewhat inappropriate. Detached breakwaters are built for two, usually independent, purposes: (1) as breakwaters to improve navigation and (2) as shore-protection devices. The first type of application primarily concerns wave sheltering at the entrance to a large harbor. The breakwater is typically several hundred to a few thousand feet long and may be located thousands of feet offshore in relatively deep water. If there is a beach in the lee of the breakwater, the shoreline may respond to the presence of the structure because of its great wave shadowing (the desired feature for navigation safety). This type of breakwater is not constructed for shoreline protection and will not be discussed further.

As a shore-protection device, a detached breakwater is typically 100 to 300 feet long, and is usually placed somewhat farther offshore than the average width of the surf zone. The important concept is that the structure is detached or separated from the shoreline and hence, in principle, sediment can pass alongshore between it and the shoreline. The amount of sediment that passes is an important factor in the functional design of a breakwater. Detached breakwaters can be built alongshore in series, analogous to a field of groins, to protect a long stretch of shoreline. Such multiple detached breakwater systems are referred to as *segmented detached breakwaters*. The length of the gap between breakwater segments becomes an important parameter, together with the length of the breakwater, its distance offshore (or, equivalently, the depth at the structure), and the wave transmission at the structure, which is discussed further below.

There are three general shoreline responses to a detached breakwater, as shown schematically in figure 11. These are a *tombolo*, a *salient*, and *limited response*. A *tombolo* is a word of Italian origin that refers to the bridge of sand or sediment that grows from the mainland beach to a detached breakwater (or to a small island or a rock outcrop that is located relatively near to shore). A *salient* is a structure-induced beach cusp that grows out

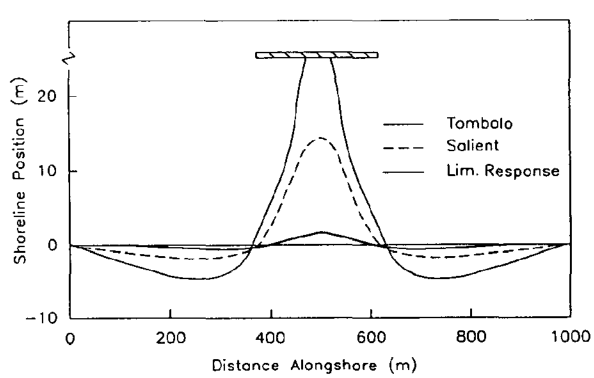


Figure 11. Schematic of shoreline response to a detached breakwater.

from the beach but reaches equilibrium size before reaching the breakwater. *Limited response* denotes either that there is no change of engineering significance in shoreline position or that there is small salient growth that is either transient or seasonal. At the beginning stage of shoreline response to a detached breakwater, the shoreline directly opposite both ends of the structure can erode. As the shoreline-breakwater system approaches equilibrium, the eroded areas will tend to fill in. If the length of the detached breakwater is large in comparison to the width of the surf zone, salients or tombolos may form at each end.

From about the 1960s, numerous detached breakwaters have been built in Japan as a preferred shore-protection measure, although in the United States a limited number of such structures were built as early as the 1930s. After a decline in use in the United States, some substantial detached breakwater projects are now being built on relatively low-wave energy coasts—6 breakwaters at Holly Beach, Louisiana (Nakashima et al. 1987, Hanson, Kraus, and Nakashima 1989) and 58 breakwaters under construction at Presque Isle, Ohio (Mohr and Ippolito 1991).

Detached breakwaters have a number of advantages over groins as a shore-protection device. If a tombolo is required (as can be created by beach fill, a common method of construction in the Chesapeake estuary, Virginia), an artificial headland is formed. If a salient is required and approximately formed by placing fill on the beach behind the structure, the majority of sand moving alongshore can pass the breakwater and move to downdrift beaches. Detached breakwaters can provide a sheltered area in the ocean beach environment for waders and swimmers who desire calmer water than that on the open coast away from the breakwater; however, a strong diffraction current directed offshore should be avoided in such an application. The diffraction current can be reduced by increasing wave transmission at the breakwater. Detached breakwaters made of rubble mound or armor blocks tend to enhance sea life and fishing, although fishing from or near breakwaters may be hazardous.

The main disadvantages of detached breakwaters are that they are expensive to construct, they are considered by many to be unaesthetic, they may reduce water quality, they prevent some portion of sand from reaching the downdrift coast, and they are a hazard to or prevent some recreational activities such as surfing. The construction costs are high because work must usually be done from a barge or trestle. In low-wave environments and seasons, it is feasible to construct a breakwater by building a sand road from shore to the site, then operating a crane from the end of the road to place the construction material. The material making up the road can then be removed or redistributed as initial fill. View degradation may be reduced by using submerged detached breakwaters (Ahrens 1989). However, wave protection decreases as the depth of submergence increases.

The *wave transmission coefficient* K_T of a breakwater is defined as the ratio of the height of the waves just seaward of the structure to the height on the landward side. The value $K_T = 0$ implies that no waves pass over or through the breakwater, and a value of K_T close to unity implies that the structure has little effect on the waves. Breakwaters built to shelter navigation are typically high and impermeable (for example, made of sand-filled concrete caissons), whereas detached breakwaters built for protecting the shore are usually designed to have some wave transmission by (1) setting the crest elevation to allow a portion of the higher waves to pass over, and (2) making the breakwater permeable to allow wave energy to pass through. Breakwaters that have low transmission coefficients experience less wave force and tend to last longer. Also, because the cost of the material composing a breakwater is proportional to the volume of the structure, hence roughly proportional to the cube of its elevation, it is economically advantageous to build low breakwaters. Figure 12 shows numerical simulations of shoreline planform behind a detached breakwater as a function of the transmission coefficient (Hanson and Kraus 1989, 1990).

Water quality problems may be reduced by increasing the gap size between breakwater segments. Areas with both low waves and low tides, such as the Mediterranean, are susceptible to water quality deterioration because of a lack of flushing. Sand blockage problems can be reduced by (1) placing fill from an upland or offshore source behind the breakwaters, (2) increasing the gap size to allow more wave energy to pass shoreward, and (3) placing the breakwaters in shallower water so that sand bypasses alongshore and around the outside of the structures during storms.

For the beach response to detached breakwaters, at least 14 parameters enter equation (1) (Hanson and Kraus 1990). The engineer can control only those parameters associated with the structure (except for sediment supply if a fill is added), and Hanson and Kraus found useful nondimensional parameters to be the length of the structure relative X to the length of the average waves at the structure L, and incident wave height in deep water H_0 relative to water depth at the structure D, and the wave transmission coefficient K_T. Figure 13 shows the results of intensive numerical simulations of shoreline change with many combinations of these variables (Hanson and Kraus 1990). It is seen that tombolo formation, salient formation, and limited shoreline response fall into distinct regions. By using this figure, prepared for a beach with 0.2-mm mean diameter sand, the planner or engineer can make a first estimate of the functional design of a detached breakwater according to the wave climate and beach slope of concern.

Sources of information on shoreline response to detached breakwaters and their functional design include the SPM (1984), Dally and Pope (1986), and Pope and Dean (1986). Recent numerical modeling simulation advances in shoreline response to detached breakwaters are described by Hanson and Kraus (1989, 1990, 1991a, 1991b).

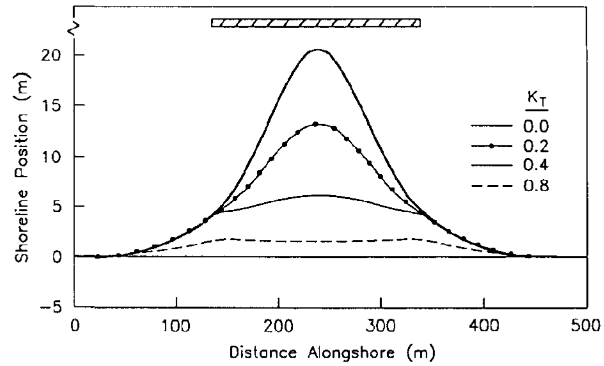


Figure 12. Calculated shoreline response at a detached breakwater for different wave transmission coefficients.

Floating Breakwaters

Floating breakwaters have been used on low-wave energy coastlines with some success to provide shoreline stabilization (Hales 1981). Floating breakwaters work by either reflecting or dissipating waves. Typical floating breakwaters are shown in figure 14. An example of a reflective floating breakwater is the pontoon section, which can be fabricated from steel, concrete, or wood. It is typically a large box section which has a draft of approximately 5 feet. This type of structure is reasonably effective at reflecting small waves. The floating tire breakwater is an example of a dissipative breakwater. Used tires are connected to form a buoyant mat. These mats of tires are then moored to float on the free surface. As the water flows through the tire modules, incident wave energy is dissipated as turbulence.

Many other types of floating breakwaters have been proposed, including submerged flaps, spheres, A-frames, and inclined pontoons. These structures have been found to be effective for relatively narrow ranges of wave conditions.

Floating breakwaters are generally less expensive to construct than conventional fixed structures such as revetments, seawalls, and rubble breakwaters. They also have the advantage of fabrication on land for towing into position. Floating breakwaters may be installed quickly to provide a rapid response to the need for protection. They may also be removed and installed seasonally, a particularly useful feature in areas where freezing occurs. Disadvantages of floating breakwaters are that they do not provide

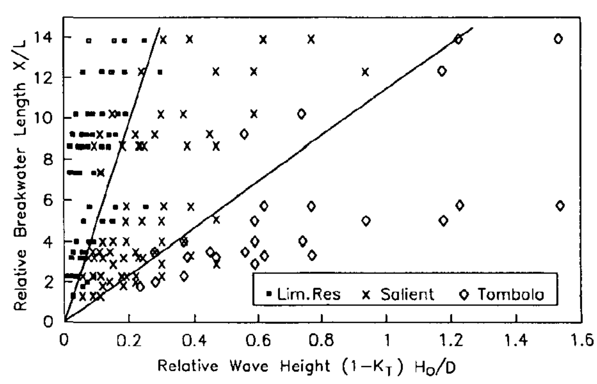


Figure 13. Classification of shoreline response to detached breakwaters.

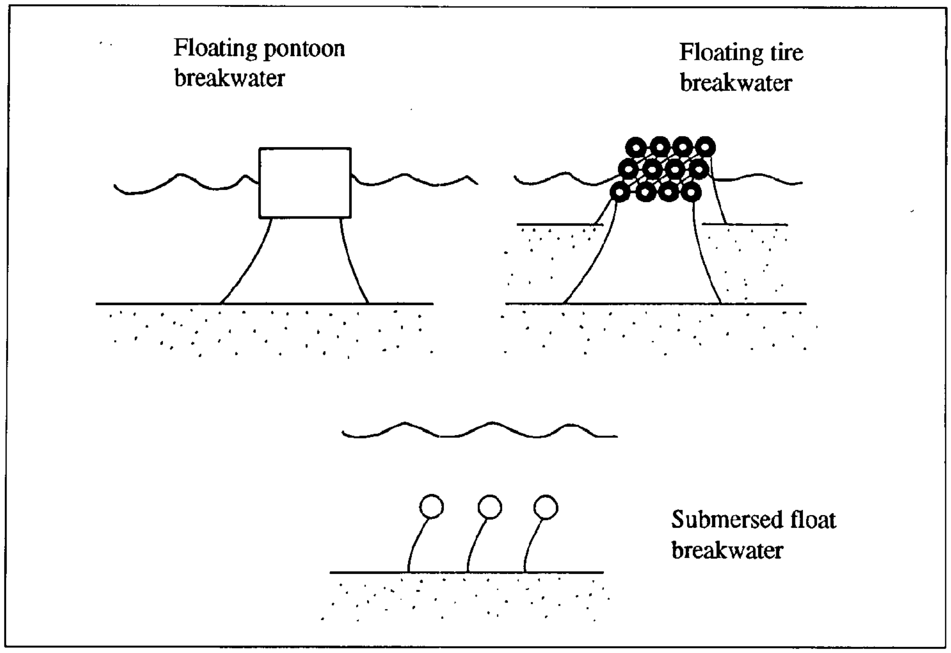


Figure 14. Examples of floating breakwaters.

protection for long-period waves, they are very difficult to moor in large seas, and they have higher maintenance requirements than other methods of stabilization. For these reasons, floating breakwaters are not a viable alternative for open-ocean applications on the Oregon coast.

Combinations of Shore-Protection Responses

Combined shore-protection measures are becoming a more common design alternative, due in part to a comprehension of the needs of both shore retention and backshore protection, and to our increased capability to develop successful functional designs. Two major examples are the combination of beach fills and groins, and beach fills and detached breakwaters. As discussed above, a groin field in which the compartments are not filled with sand will result in a significant reduction of sediment supply to the downdrift beaches. The same downdrift losses of sediment will also occur for offshore breakwaters that are not properly filled with sediment. For these two structural alternatives to be viable in comprehensive planning, they must be combined with beach fills.

Another combination example is a *perched beach.* In this case a very low submerged breakwater, or sill, is built in the offshore. This small structure will somewhat reduce incident wave energy into the surf zone, tending to stabilize the sand on the beach. In addition, a beach fill is placed so that its seaward end is supported by the sill or submerged breakwater, as sketched in figure 15. The perch can be constructed as a rubble structure or as a concrete structure using prefabricated modules. However, sand moving offshore and over the sill cannot jump the sill and return.

A low breakwater supporting a perched beach will not significantly reduce large waves. In this case, a substantial portion of the fill may be lost,

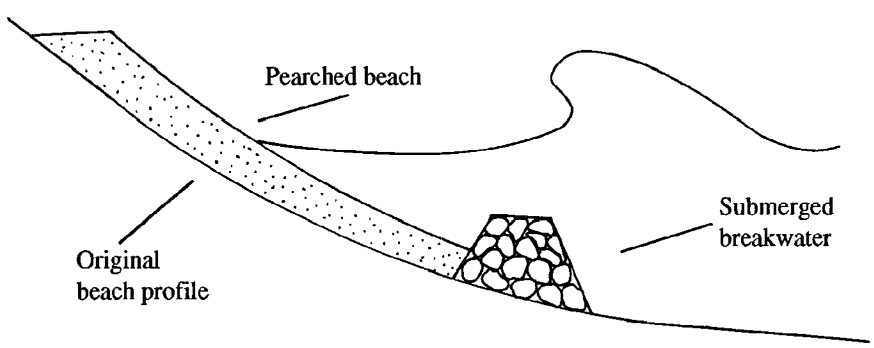


Figure 15. Schematic of a perched beach.

and the backshore may erode. Therefore, a small revetment can be placed beneath the fill that would be visible and provide protection only in extreme events. Because the waves are somewhat reduced by the submerged breakwater, the size of the revetment could be less substantial than an exposed revetment. For relatively low energy conditions, a number of commercially available prefabricated concrete mats are available. They may be installed by hand before the fill is placed.

Structures at the ends of littoral cells can reduce loss of sand from the cell, and some portion of this sand can be either bypassed or backpassed, according to the situation. Beach-quality sand dredged from navigation channels may be placed directly on shore or in the form of linear bars in the offshore. Such mounds of sand function similar to a highly transmissive detached breakwater, but one that may also deflate and supply sand to the littoral system and beach.

Concluding Discussion

This paper has given an integrated overview of shore-protection engineering alternatives. Citations in the text direct the interested reader to more detailed technical information. Most alternatives have a large experience base in case studies, and literature on numerical simulation of beach evolution under single and combined alternatives is also available.

In approaching a shore-protection problem, planners should determine whether they want a shore-protection alternative to function as shore retention or backland protection. Table 1 below summarizes the applicability of each major category of alternative, together with an estimate of the relative cost for typical situations. Site-specific circumstances (for example, availability of material such as fill and accessibility to the site) may alter the relative cost.

In a comprehensive coastal management plan, which is one that covers a regional scale (at least the littoral encompassing the site and a reasonable project life cycle), a combination of the above alternatives is probably necessary for a balance between shore retention and backland protection.

Acknowledgment

We are grateful for the cooperation of the individuals who supplied photographs for this work, as acknowledged in the figure captions. We thank Dr. Clifford Truitt for informative discussions and review of this paper. The work of N.C.K. was conducted at the Coastal Engineering Research Center, U.S. Army Waterways Experiment Station, as an activity of the Beach Fill Engineering work unit of the Coastal Program, U.S. Army Corps of Engineers. He appreciates permission granted by Headquarters, Chief of Engineers, to publish this information.

References

Ahrens, J.A. 1989. Stability of Reef Breakwaters, Journal of Waterway, Port, Coastal and Ocean Engineering, 115, 221-234.

Alternative	Shore Retention	Backland Protection	Cost
Relocation	High	Low	High (developed area); Low (undeveloped area)
Beach nourishment	High	Low to high	Medium to high
Revetments	Low	High	Medium to high
Seawalls	Low	High	High
Groins	High	Low to medium	Low to medium
Detached breakwaters (fixed)	Medium to high	Low to medium	Medium to high
Detached breakwaters (floating)	Medium	Low	Low to medium

Table 1. Summary of shore-protection alternatives.

Balsille, J.H. and Berg, D.H. 1972. State of groin design and effectiveness, Proceedings of 13th Coastal Engineering Conference, American Society of Civil Engineers, 1367-1383.

Beach Erosion Board. 1954. Shore protection, planning and design, Technical Report 4, U.S. Army Corps of Engineers, Washington, D.C.

Clausner, J.E., Gebert, J.A., Rambo, A.T., and Watson, K.D. 1991. Sand bypassing at Indian River Inlet, Delaware, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 1117-1191.

Clemens, K.E. and Komar, P.D. 1988. Tracers of sand movement on the Oregon coast, Proceedings of 21st Coastal Engineering Conference, American Society of Civil Engineers, 1138-1351.

Corps of Engineers. 1972. The Role of Vegetation in Shoreline Management, 32 pp.

Corps of Engineers. 1980. Low Cost Shore Protection—A Property Owners Guide, 159 pp.

Dally, W.R. and Pope, J. 1986. Detached breakwaters for shore protection, Technical Report CERC-86-1, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Dean, R.G. 1984. Principles of beach nourishment, in: P.D. Komar (Editor), Handbook of Coastal Processes and Erosion, CRC Press, Inc., Boca Raton, Fla., 217-231.

Dean, R.G. 1986. Coastal armoring, effects, principles and mitigation, Proceedings of 20th Coastal Engineering Conference, American Society of Civil Engineers, 1843-1857.

Dean, R.G. 1991. Equilibrium beach profiles: characteristics and applications, Journal of Coastal Research, 7(1), 53-84.

Gravens, M.B. and Kraus, N.C. 1989. Representation of groins in numerical models of shoreline response, Proceedings of XXIII Congress, Hydraulics and the Environment, International Association for Hydraulic Research, C515-C522.

Griggs, G.B., Tait, J.F., Scott, K., and Plant, N. 1991. The interactions of seawalls and beaches: four years of field monitoring, Monterey Bay, California, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 1871-1885.

Hales, L.Z. 1981. Floating Breakwaters: State-of-the-Art Literature Review, Technical Report No. 81-1, Coastal Engineering Research Center, Vicksburg, Miss., 279 pp.

Hanson, H. and Kraus, N.C. 1989. GENESIS: Generalized Model for Simulating Shoreline change, Report 1: Technical Reference, Technical Report CERC-89-19, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Hanson, H. and Kraus, N.C. 1990. Shoreline response to a single transmissive detached breakwater, Proceedings of 22nd Coastal Engineering Conference, American Society of Civil Engineers, 2034-2046.

Hanson, H. and Kraus, N.C. 1991a. Numerical simulation of shoreline change at Lorain, Ohio, Journal of Waterway, Port, Coastal and Ocean Engineering, 117(1), 1-18.

Hanson, H. and Kraus, N.C. 1991b. Comparison of shoreline change obtained with physical and numerical models, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 1785-1799.

Hanson, H., Kraus, N.C., and Nakashima, L.D. 1989. Shoreline change behind transmissive detached breakwaters, Proceedings of Coastal Zone '89, American Society of Civil Engineers, 568-582.

Hobson, R.D. 1977. Review of design elements for beach-fill evaluation, Technical Paper No. 77-6, U.S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Miss.

Hotta, S., Kraus, N.C., and Horikawa, K. 1987. Function of sand fences in controlling wind-blown wind, Proceedings of Coastal Sediments '87, American Society of Civil Engineers, 772-787.

Hotta, S., Kraus, N.C., and Horikawa, K. 1991. Functioning of multi-row sand fences in forming foredunes, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 261-275.

Jensen, R.E., Hubertz, J.M., and Payne, J.B. 1989. Pacific coast hindcast Phase III North Wave Information, WIS Report 17, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Komar, P.D. 1986. El Niño and erosion on the coast of Oregon, Shore and Beach, 54, 3-12.

Komar, P.D. 1978. Wave conditions on the Oregon coast during the winter of 1977-78 and the resulting erosion of Nestucca Spit. Shore and Beach 46:3-8.

Komar, P.D. 1991. Ocean processes and hazards along the Oregon coast, present workshop volume.

Komar, P.D. and J.W. Good. 1989. Long-term impacts of the 1982-83 El Niño on the Oregon Coast, Proceedings of Coastal Zone '89, American Society of Civil Engineers, 3785-3794.

Komar, P.D., J.W. Good, and S.M. Shih. 1989. Erosion of Netarts Spit, Oregon: continued impacts of the 1982-83 El Niño, Shore and Beach, 57, 11-19.

Komar, P.D. and McDougal, W.G. 1988. Coastal erosion and engineering structures: the Oregon experience, in: Kraus, N.C. and Pilkey, O.H. (Editors), Journal of Coastal Research, Special Issue No. 4, The Effects of Seawalls on the Beach, 77-92.

Komar, P.D. and Rae, C.C. 1976. Erosion of Siletz Spit, Oregon, Shore and Beach, 44, 9-15.

Komar, P.D. and S.M. Shih. 1991. Sea-cliff erosion along the Oregon coast, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 1558-1570.

Kraus, N.C. 1983. Applications of a shoreline prediction model, Proceedings of Coastal Structures '83, American Society of Civil Engineers, 632-645.

Kraus, N.C. 1987. The effects of seawalls on the beach: a literature review, Proceedings of Coastal Sediments '87, American Society of Civil Engineers, 945-960.

Kraus, N.C. 1988. The effects of seawalls on the beach: an extended literature review, in: Kraus, N.C. and Pilkey, O.H. (Editors), Journal of Coastal Research, Special Issue No. 4, The Effects of Seawalls on the Beach, 1-28.

Kraus, N.C. 1989. Beach change modeling and the coastal planning process, Proceedings of Coastal Zone '89, American Society of Civil Engineers, 553-567.

Kraus, N.C. (Editor), 1990. Shoreline change and storm-induced beach erosion modeling, a collection of seven papers, Miscellaneous Paper CERC-90-2, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Kraus, N.C. and Larson, M. 1988. Prediction of initial profile adjustment of nourished beaches to wave action, Proceedings of Beach Preservation Technology '88, Florida Shore and Beach Preservation Association, Inc., 125-137.

Kraus, N.C., Larson, M., and Kriebel, D.L. 1991. Evaluation of beach erosion and accretion predictors, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 572-587.

Kraus, N.C. and Pilkey, O.H. 1988. (Editors). The Effects of Seawalls on the Beach, Journal of Coastal Research, Special Issue No. 4, 146 pp.

Larson, M., Hanson, H., and Kraus, N. C. 1987. Analytical solutions of the one-line model of shoreline change, Technical Report CERC-87-15, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Larson, M. and Kraus, N.C. 1989a. Prediction of beach fill response to varying waves and water level, Proceedings of Coastal Zone '89, American Society of Civil Engineers, 607-621.

Larson, M. and Kraus, N.C. 1989b. SBEACH: Numerical model for simulating storm-induced beach change, Report 1: empirical foundation and model development, Technical Report CERC-89-9, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Larson, M. and Kraus, N.C. 1991. Mathematical modeling of the fate of beach fill, in: H.D. Niemayer, J. van Overeem, and J. van de Graaff (Editors), Artificial Beach Nourishments, Special Issue of Coastal Engineering, Vol. 16, pp. 83-114.

McDougal, W.G., Sturtevant, M.A., and Komar, P.D. 1987. Laboratory and field investigation of the impact of shoreline stabilization structures on adjacent properties, Proceedings of Coastal Sediments '87, American Society of Civil Engineers, 961-973.

McLellan, T.N. 1990. Nearshore mound construction using dredged material, J. Coastal Research, Special Issue No. 7, 99-107.

McLellan, T.N. and Kraus, N.C. 1991. Design guidance for nearshore berm construction, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 2000-2011.

Mohr, M.C. and Ippolito, M. 1991. Initial shoreline response at the Presque Isle erosion control project, Proceedings of Coastal Sediments '91, American Society of Civil Engineers, 1740-1754.

Nakashima, L.D., Pope, J., Mossa, J. and Dean, J.L. 1987. Initial response of a segmented breakwater system at Holly Beach, Proceedings of Coastal Sediments '87, American Society of Civil Engineers, 1399-1414.

Pope, J. and Dean, J.L. 1986. Development of design criteria for segmented breakwaters, Proceedings of 20th Coastal Engineering Conference, American Society of Civil Engineers, 2144-2158.

Richardson, T.W. 1991. Sand bypassing, in: Herbich, J. B. (Editor), Handbook of Coastal and Ocean Engineering, Vol. 2, Gulf Pub. Co., Houston, Texas, 808-828.

Shore Protection Manual. 1984. (2nd ed.) 2 Vols., Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Washington, D.C.

Shows, E.W. 1978. Florida's coastal setback line—an effort to regulate beachfront development, Coastal Zone Management Journal, 4(1-2), 151-164.

Sunamura, T. 1984. Principles of sea cliff and platform erosion, in: P.D. Komar (Editor), Handbook of Coastal Processes and Erosion, CRC Press, Inc., Boca Raton, Fla., 233-265.

Walton, T.L. and Sensabaugh, W. 1978. Seawall Design on Sandy Beaches, University of Florida Sea Grant Report, No. 29, 24 pp.

Weggel, J.R. 1988. Seawalls: the need for research, dimensional considerations and a suggested classification, in: Kraus, N.C. and Pilkey, O.H. (Editors), Journal of Coastal Research, Special Issue No. 4, The Effects of Seawalls on the Beach, 29-39.

Williams, S.J., Dodd, K., and Gohn, K.K. 1991. Coasts in crisis, U.S. Geological Survey 1075, 32 pp.

A Discussion of "Shore Protection and Engineering with Special Reference to the Oregon Coast"

Spencer M. Rogers, Jr.
Department of Civil Engineering, North Carolina State University, and
UNC Sea Grant Marine Advisory Service

Relocation, the first of the four general shore-protection responses discussed in the previous paper, by Kraus and McDougal, can be broadened to more clearly include planning and management options such as setback lines, which are discussed elsewhere in the paper. Relocation implies that the facility was planned for a location sufficiently threatened by erosion to eventually require movement to a less hazardous location. *Avoidance* is a broader category that can include initial siting decisions to (1) avoid the hazard for the useful life of the facility, (2) avoid the hazard for a planned period, at which time relocation can be used to extend the functional life of the facility, or (3) relocate to avoid the hazard if there was no planning or if the hazard was initially underestimated.

As discussed by the previous authors, design lifetimes of 50 years are often used in building codes and coastal protection designs. However, a design lifetime is often different from a useful lifetime. For example, many buildings are designed for 50-year wind speeds. After determining the predicted forces, the designer adds a safety factor to the forces before selecting proper materials and sizes. The designer, at least for buildings, gives his or her assurance that the building should withstand reasonably predicted conditions for at least 50 years. Because of the safety factors, the ultimate strength of the building can be expected to survive much worse conditions.

One practical effect for buildings is that they often last longer than a 50-year design life. The average useful lifetime of a wood-frame house in the U.S. is about 70 years (Anderson 1978) and slightly longer for larger buildings or other construction materials.

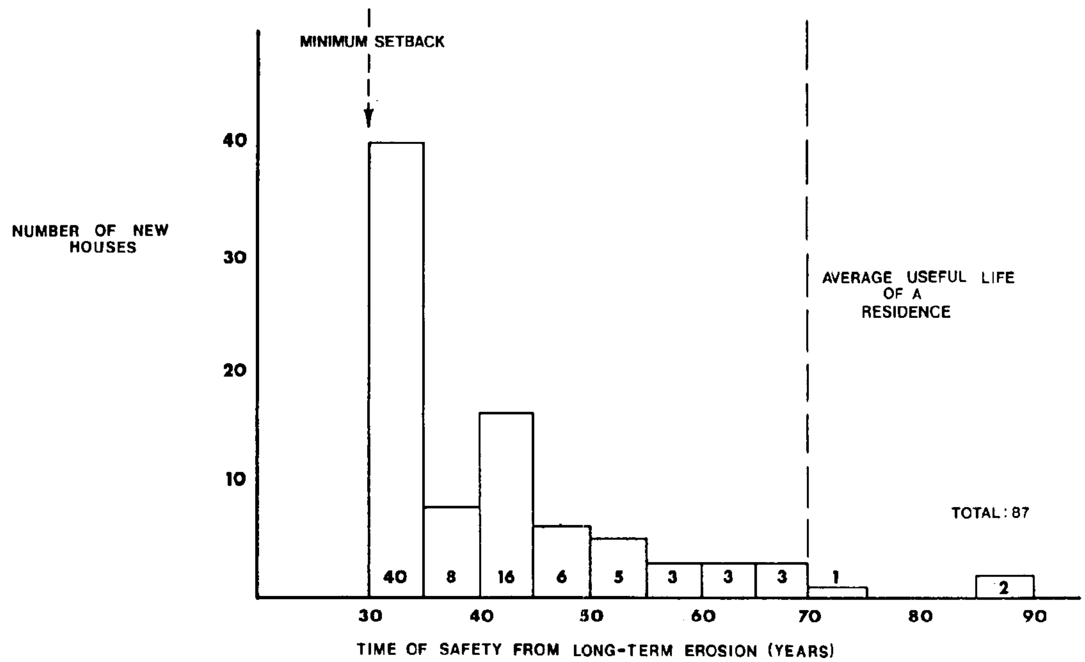
Either voluntary or regulatory setbacks based on predicted erosion rates are clearly useful tools to avoid the need for other shore-protection alternatives. To be effective, the setbacks must be large enough to protect the building for its entire useful life. Given the uncertainties of long-term erosion prediction, a significant safety factor (for example, an increased setback distance) should be included. For a wood-frame house with a 70-year useful lifetime, a 100-year erosion setback might be an appropriate minimum to effectively use avoidance for shore protection.

For a variety of practical and political reasons, such large setbacks are not feasible on many shorelines with significant erosion rates. Relocation must therefore be anticipated when smaller setbacks are used. For example, North Carolina's coastal management regulations require minimum oceanfront setbacks of 30 times the annual erosion rate for small buildings and 60 times for large buildings. Congress is currently considering similar legislation as an amendment to the National Flood Insurance Program. Small buildings can be designed to be relatively easy to relocate. A larger setback is imposed on larger buildings because of the greater engineering difficulty and the cost of relocation.

Small buildings have been moved away from erosion threats routinely in North Carolina. To date, no large buildings have been sufficiently threatened to justify moving. With a 60-year setback and North Carolina's ban on stabilization structures, it is inevitable that the regulations will be tested by threatened large buildings in the future.

Minimum erosion-based setback lines clearly force some development farther away from the shoreline. But setbacks can have other less obvious and sometimes undesirable effects as well. Stutts, Siderelis, and Rogers (1985) looked at property owner response to the first two years of

Figure 1.



the 30-year setback in four North Carolina communities. By measuring the actual distance owners chose as a setback and dividing by the annual erosion rate, the researchers determined the relative level of erosion safety for each new building. Thirty percent of the owners chose to build as close as possible on the 30-year minimum. Half the owners chose to build with fewer than 35 years of erosion safety, as shown in figure 1. Only 3 percent located with erosion safety levels greater than 70 years. In some cases the property lacked sufficient depth to locate farther landward. But where room was available, three-quarters of the owners chose to use more of the extra buildable depth to build farther away from the street setback than from the ocean setback.

Many factors, including the perceived threat of erosion, influence the decision on where to locate development on a specific property. One of the undesirable effects of establishing regulated setbacks significantly less than the useful life of the building is that some owners will be encouraged to build farther seaward. It is common in many forms of regulation that when minimum standards are established, they become *the* standard, neglecting the minimum intent. If the level of the standard is high compared to the useful life of the action, there are few problems. For example, a 100-year flood design or, with appropriate safety factors, a 50-year wind design, compares well with the 70-year average useful lifetime of a house. The 30-year erosion setback is far less than the useful life. Property owners appear to reason that "If the regulations allow us to build this close to the ocean, it must be safe," rather than "If located here, the building will fall in the ocean in 30 years." Regardless of the educational efforts of the regulators, the minimum seems to become the norm.

Use of a minimum setback when there is room farther landward on the property can cause problems even for owners committed to avoidance or relocation. On property lacking unlimited depth for relocation, leaving smaller distances on the landward side of the building may make it unfeasible to use the area when relocation is eventually needed. Initial construction as far landward as possible might provide an additional 5 or 10 years of use beyond the minimum setback location. But once a building is constructed at the minimum, the owner cannot justify the expense of relocating it the short distance to the back of the property. Relocation would then require purchase of another building site. When relocating a building, the owner usually must comply with the erosion setbacks at the time of the move. By the time relocation is necessary, erosion can move the minimum setback far enough inland to prohibit relocation on the same lot even if the owner wishes to relocate there.

The use of erosion setbacks significantly smaller than the lifetime of the development is often a political reality, given the shallow buildable depth available along much of the subdivided shoreline and given the desire to avoid legal challenges on the taking issue. To make the best use of avoidance or relocation regulations, it is more effective to require setbacks comparable to the lifetime of the development, but, if necessary, to make exceptions that allow owners to build farther seaward when the building is planned as far landward as the property will allow.

Avoidance can be broadly interpreted to include the use of appropriate construction techniques that are not explicitly addressed in the four possible shore-protection responses. Erosion-based setbacks are not effective in preventing damage to coastal buildings during infrequent but extreme storm events, particularly in areas with low long-term erosion or on low ground elevations likely to be overtopped by storm conditions (Rogers 1990). For example, without stringent construction standards, there is no safe place to build on spits or barriers. However, in such cases properly designed methods for building construction or other shore-protection options can be effective.

Extreme storm events cause waves, storm tides, and erosion at locations well inland from areas of normal shoreline fluctuations. The normal design philosophy for extreme events, particularly in small buildings, can be considered avoidance of waves. Typical designs incorporate open piling foundations above any anticipated wave action and enough piling penetration to tolerate any wave-induced erosion.

In summary, avoidance using erosion-based setbacks can be a useful tool for shore protection. However, the use of setbacks with shorter lifetimes than the useful lifetime of the development is often misunderstood by owners and may encourage some to locate as far seaward as the minimum setback will allow. For avoidance to be effective, owners must truly understand the erosion hazard and have a plan for relocating when necessary. At locations where smaller setbacks must be applied, it is better to use the maximum feasible setback and thus use the assets of the property to best advantage.

References

Anderson, C.M. 1978. Coastal residential structures life term determination. National Association of Home Builders Research Foundation, Inc., Rockville, Maryland.

Rogers, S.M., Jr., 1990. Designing for storm and wave damage in coastal buildings. Proceedings for the Coastal Engineering Conference. American Society of Civil Engineers, pp. 2908-2921.

Stutts, A.T., Siderelis, C.D., and Rogers, S.M., Jr. 1985. Effect of ocean setback standards on the location of permanent structures. Proceedings of Coastal Zone '85, American Society of Civil Engineers, pp. 2459-2467.

PUBLIC POLICY

SHORE PROTECTION AND ENGINEERING

Responding to Oregon's Shoreline Erosion Hazards: Some Lessons Learned from California

Gary B. Griggs
Institute of Marine Sciences, University of California, Santa Cruz

Introduction

The geological hazards along the coastlines of California and Oregon are similar in many respects. Earthquakes and tsunamis represent large-scale threats that occur relatively infrequently. Bluff failure, shoreline erosion, and storm wave inundation, on the other hand, produce less overall damage per event, but are more frequent occurrences. One major difference between the two states is that California has 10 times as many people (1990 census of just over 30,000,000) and that the oceanfront area of southern and much of central California has been intensively developed (figure 1). The Oregon coast, in contrast, has been, until recently, relatively undeveloped, although this has slowly begun to change.

The goal of all of those involved with coastal geologic hazards should be to reduce the number of people, as well as dwellings, structures, and utilities, both public and private, directly exposed to the hazards of shoreline erosion, wave impact, and inundation. Although progress has been made in reducing both public and private exposure to coastal hazards in California over the past several decades, particularly since the passage of the California Coastal Initiative in 1972, major problems remain. Serious policy gaps exist in the State Coastal Act. State agencies continue to fund or undertake questionable coastal protection projects. Wide variation in interpretation and implementation of the Coastal Act by local governments raises important questions regarding the actual level of coastal resource protection achieved under current state policies.

At the time the Coastal Initiative was passed by the California voters, it was widely acknowledged that local governments, acting incrementally and in isolation from each other, could not adequately address the various problems occurring along the state's ocean shoreline. It was this very fact that led to the creation of the California

Figure 1. Oceanfront home development along the cliff and beach of southern California near Malibu.

Coastal Zone Conservation Commission and its mandate to prepare a statewide plan for the permanent protection of the remaining natural and scenic resources of the coastline.

California's coastal hazards and its policies relating to coastal hazards and hazard protection have been the subjects of considerable recent research (Griggs et al. 1991; Griggs and Fulton-Bennett 1988; Griggs 1987a; Fulton-Bennett and Griggs 1986; Griggs and Savoy 1985). It is believed that the experience gained from California should be of value to coastal hazard geologists, coastal engineers, and coastal planners in Oregon.

Hazardous Coastal Environments

The coastline is a dynamic and ever-changing environment. Changes occur both over short time intervals (for example, the changes from a single storm) and over longer intervals (the progressive erosion of a particular unstable bluff area over a number of years, for example). Both types of changes can affect a property or building, and individuals should seriously evaluate both before investing their life savings. The wide protective summer beach can disappear quickly during a major storm, and before long the concrete patio or redwood deck has been undercut by waves (figure 2). Many oceanfront residents have discovered too late that sliding glass doors and half-inch thick plywood siding are no match for the large driftwood logs thrown about by the surf crashing through their front yards.

Two areas of major concern that need to be addressed are the particular site itself and the structure, either existing or proposed. Considering both the hazards that affect coastal areas and the very high cost of oceanfront property, anyone contemplating such an investment is strongly advised to hire a professional with experience in the coastal zone to evaluate the stability of the property and its structures. Along the California coast there are three particular physical environments where widespread development has taken place but that are potentially hazardous. These same environments occur along the coast of Oregon. They are (1) the beach, (2) the dunes, and (3) eroding cliffs or unstable bluff tops.

Identifying Coastal Hazards

With any oceanfront area or environment, there are two different situations to consider—undeveloped property and developed property. With undeveloped property, the opportunity

Figure 2. Beach levels have been lowered approximately five feet due to a combination of high tides and storm waves to undercut this deck and expose foundations in northern Monterey Bay, California.

exists to carefully evaluate the hazards, both short and long term, and the risks they pose prior to any development of the land. In California, the nature and the scope of the site investigation that is required prior to approval of any oceanfront development are legislated by local governments, although in principle, these are, over time, supposed to come into conformance with the State Coastal Act. In a detailed investigation of state coastal hazard policies in California (Griggs et al. 1991), it became clear that the 15 counties and 35 cities had established very different requirements, standards, policies, and practices, as a result of the paucity of state coastal hazards policy and the considerable ambiguity and latitude of applicable state guidelines. As a result there is a wide variety of approaches to coastal natural hazards among local governments as well as state agencies.

Nonetheless, with adequate and competent site investigation, the hazards and risks posed by geologic processes to any oceanfront parcel, whether it be beach, dune, or bluff, can be identified, evaluated, and incorporated into the planning process. With adequate safeguards, which may include a range of approaches, including setbacks, engineered foundations, elevating, runoff, and groundwater control, or complete relocation, these risks can be reduced to an acceptable level. In this way, we can eliminate the need for a coastal protection structure or an emergency response in the future. This is clearly the favored approach and would result in the lowest long-term public and private costs. In California, over the past decade, the losses and costs of shoreline protection, storm damage, and other expenses related to oceanfront development have averaged nearly $100 million annually. These are losses and expenses that Oregon can avoid with careful siting of any new development, whether public or private.

In contrast to undeveloped land are those properties which are already developed in potentially hazardous oceanfront locations. A careful look at the Oregon coast will make it clear that, even with a relatively undeveloped shoreline, there are a number of old and also recent examples where the hazardous nature of the site either was not recognized or was disregarded in the siting of development.

Responses to Coastal Hazards

Over the past 50 years, the principal response to coastal hazards in California has been the construction of structures—seawalls and rip-rap revetments for the most part—designed to protect eroding or wave-affected shorelines. Protective devices have usually been constructed only after existing shoreline development have become at risk. Rarely in the past did such a protection strategy precede development. At present, however, some of California's coastal municipalities require a protective structure as a condition for development of oceanfront property. In striking contrast, other communities will not allow development in locations where a protective device would be necessary in order to insure the survival of the property through the design life of the structure.

In recent years, the growing recognition of the limitations and impacts of "hard" protective structures or armor has led to the consideration and implementation of "soft" approaches, such as beach nourishment. Moreover, the high capital and maintenance costs of protective structures have led to the economic justification of physically relocating structures away from hazardous areas (Griggs 1986).

Development Relocation

Relocation of oceanfront structures or utilities is being given increasing consideration in a number of situations. Where a parcel is large enough, a threatened structure can be moved landward on the same property to extend the period of protection, depending on the erosion rates. In many cases this will not be possible, and relocation will require acquisition of a separate lot. Recent comparisons of the cost of relocation or reconstruction and the cost of protection have indicated that in the long run, relocation may be far less expensive (Griggs 1986). Typical house-moving costs for a moderate-sized residential structure may be in the range of $10,000 to $25,000, whereas construction and maintenance of a protective seawall may be several or up to 10 times as high over the life of the residence. It is likely that this option has not been seriously considered by most threatened oceanfront property owners, simply because of the desire to protect their home and view at any cost. Some coastal communities have begun to require that shorefront homes be designed and built in such a manner that they can be easily relocated or moved in the future, thus reducing the cost of this approach.

Beach Nourishment

Nourishment, or beach replenishment, has emerged as an appealing "soft" approach to dealing with the problems of shoreline erosion. On the surface this strategy presents an attractive compromise to the extremes of abandoning the shoreline on the one hand, or armoring it with concrete or rock on the other. The beach is nourished or replenished with sand from either an offshore or inland source. The goal is to increase the width of the beach such that it serves as a more effective buffer and protects the shoreline from wave attack, thereby reducing erosion.

While in theory beach nourishment represents a more "natural" approach to the problem of shoreline erosion, there are many considerations that owners must address before embarking on any large-scale nourishment project (Leonard et al. 1989). Availability of large volumes of sand of the appropriate grain size is one of the first issues to be resolved, as is the impact of sand removal and transport. In order to add a volume of sand to a beach equivalent to a typical California annual littoral drift rate of 300,000 cubic yards, a 10-cubic-yard dump truck delivering sand 24 hours a day, 365 days a year, would have to arrive every 17 minutes. The economics of a large-scale beach nourishment effort and the distribution of costs also pose major questions for this approach to coastal protection.

The most accepted view at present is that Oregon beaches are parts of individual littoral cells trapped between major volcanic headlands, and that little littoral transport or exchange of sand takes place between cells. If this is true then replenishing sand might be a more reasonable approach in Oregon, where sand would have a longer lifespan, than on California beaches, with their high rate of littoral drift. Sand presumably continues to reach the shoreline today from river and cliff sources, yet the beaches are not growing wider. There are clearly sinks for this littoral sand, and these sinks (whether onshore or offshore) need to be carefully studied and the rates of loss quantified to the degree possible, prior to considering nourishment as a solution to Oregon's shoreline erosion problems.

Armoring or Hard Protection Structures

Historically, the most common approach to protecting private or public structures or utilities from coastal erosion has been the construction of some type of "hard" protection structure. In California, as of 1990, 130 miles, or 12% of the entire shoreline, had been armored or protected by some form of hard protective structure (figure 3).

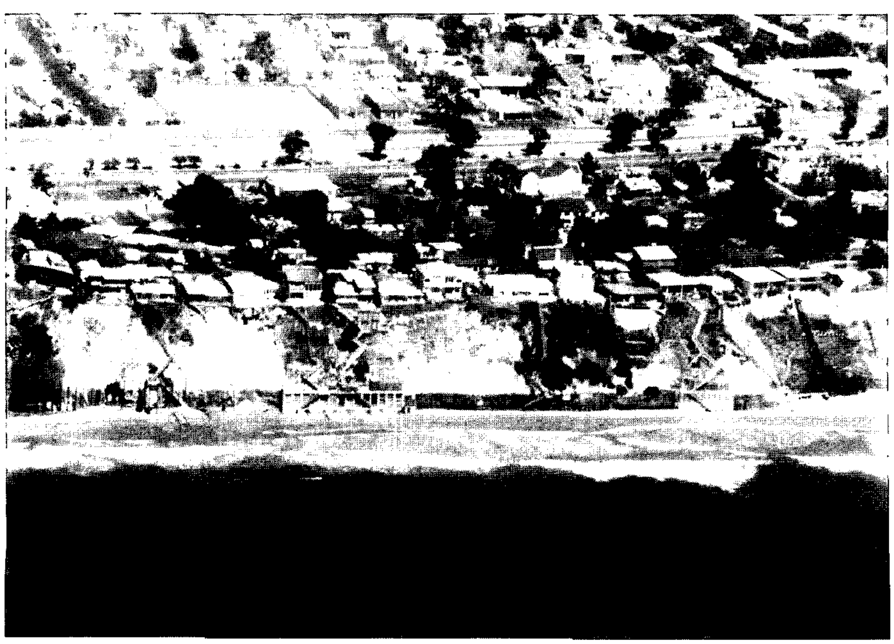


Figure 3. The construction of continuous seawalls has taken place at the base of this developed southern California bluff.

Protective structures can vary considerably in cost, size, effectiveness, and life span (Fulton-Bennett and Griggs 1986). At one extreme, slabs of broken concrete or asphalt or other construction materials have simply been dumped at the base of cliffs in an attempt to reduce the impact of waves. Most efforts of this sort have been relatively futile or very short lived. At the other extreme are massive, carefully engineered and expensive concrete seawalls, which may stand for 30 or 40 years or more (figure 4). What should be made clear at the onset, however, is that on a rapidly eroding shoreline, any protective structure built to withstand direct wave attack will probably fail eventually. Even a well-designed structure is likely to fail once its design life has been exceeded, especially if it has not been properly maintained. Engineers commonly think in terms of a 20- to 25-year life of a coastal protection structure. This should be clearly understood by the homeowner, but often is not.

Spending large amounts of money on the installation of a coastal engineering structure does not guarantee long-term, or in some cases, even short-term, protection for home and property. The exposure of a property to wave attack, the presence and width of a protective beach, and the specific design, construction, and dimensions of the structure will all influence its effectiveness.

During exceptional high tide and storm wave conditions, such as those during the El Niño of the 1982-83 winter, protective structures which have survived for decades may fail virtually overnight. Some protective structures have fared far better than others. Our research in California indicates that for most types of structures, there are a number of precautions, alterations, or design criteria which, if used, can significantly improve the structure's effectiveness or extend its lifespan.

Concrete Rubble

Broken concrete and other construction debris are some of the oldest and cheapest, but least effective, materials that have been dumped over seacliffs and onto beaches with the intent of protecting coastal property. These materials generally consist of loose dirt, flat concrete or asphalt slabs of various sizes, or small stones or bricks. At some places, concrete slurry has been added to the debris, increasing its strength but not necessarily its stability.

Because rubble is often used during emergency situations and is seldom engineered, its costs are difficult to determine. Since the material is usually free and is often simply dumped at the shoreline, its cost depends primarily on the price of hauling the material to the site. However, except during low wave conditions, or where very

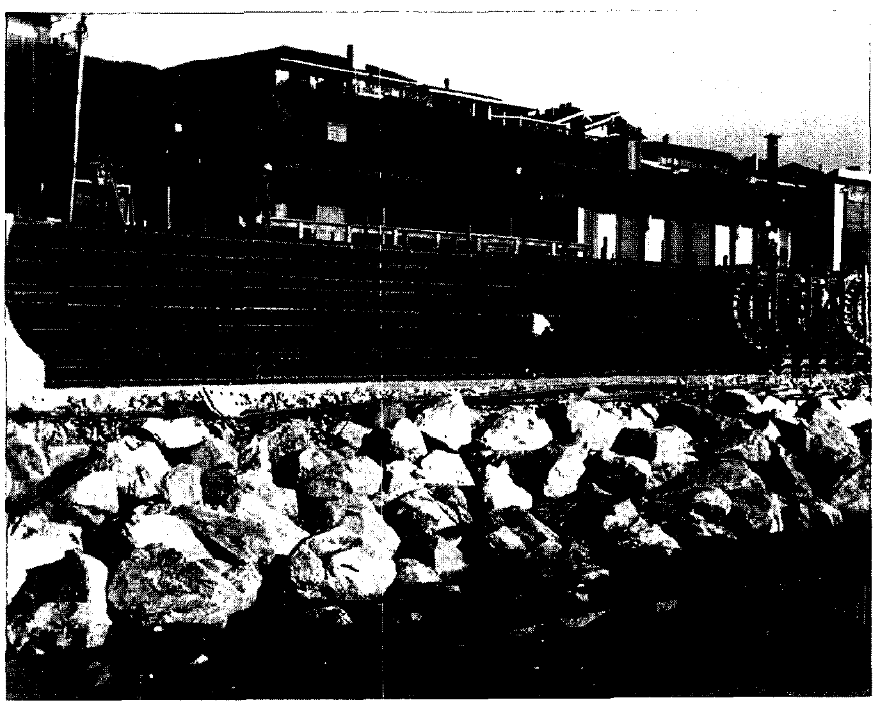


Figure 4. Construction of a curved-face concrete seawall near Santa Cruz at a cost of approximately $3000/front foot.

large volumes are used, the benefits of this type of "protection" are also very low. It fact, the use of concrete rubble may generate unexpected costs, first because it gives the appearance of protection, leading to a false sense of security and greater investment in endangered property, and second, because it must often be removed before any engineered structure can be built at the site. Its use as a core stone in riprap walls is also of questionable value, unless its size and shape can be carefully controlled. Even then, it may be easily displaced or removed, when the armor rock shifts or settles.

Riprap

Riprap revetments (engineered and nonengineered) are by far the most common structures used for protecting coastal property along the California coast. In this paper, riprap is used as a general term, referring to any large (usually 1- to 5-ton) rocks used for coastal protection. Until the late 1970s, such rocks were often just dumped over seacliffs or on top of the sand in front of endangered coastal property. This practice is still common during emergency situations. The resulting structures are usually referred to as rubble revetments or riprap seawalls, or as nonengineered riprap. Engineered riprap, in contrast, incorporates a carefully excavated foundation or keyway, filter cloth, and carefully placed layers of different sizes of rock. It has been used and required with increasing frequency over the past decade. Engineered riprap is normally designed according to explicit assumptions regarding storm waves, scour depths, and water levels. Although nonengineered riprap is more likely to be structurally damaged over time, both types can be susceptible to the same types of failure during storms.

In general, along the central California coast, we observed that the success rate of riprap walls is marred by relatively high repair and maintenance requirements and by the fact that significant property damage often occurs when these walls suffer even partial failure (Fulton-Bennett and Griggs 1985). At virtually every location where riprap has been founded on sand, in contrast to a bedrock foundation, it has settled into that sand over time. This settlement is often accompanied by a seaward movement of rocks at the toe of the structure. Such seaward movement is the result of a gradual or rapid undermining of the toe stones, which causes them to rotate seaward (figure 5). The rate and amount of riprap settling vary considerably from one location to another. Often, corners, end sections, and other localized segments of a single wall will settle, while the rest of the wall remains more or less intact.

The second common failure mode for riprap has been described as sliding, toppling, rolling, or plucking, and occurs when waves mobilize one or more armor stones in a wall, allowing them to move down to a new position of temporary stability. To prevent this type of failure, Moffat and Nichols (1983) recommend avoiding smooth, rounded, elongate, or flattened stones, and carefully placing rocks so that they interlock with one another and do not protrude from the face of the structure more than 18 inches. The *Shore Protection Manual* (U.S. Army Corps of Engineers 1977) recommends that all riprap subject to breaking waves be stacked at a slope no steeper than 1.5:1 (1.5 horizontal to 1 vertical, or 35 degrees). Although a steeper wall will encroach less far onto the beach and initially will require less rock, such a wall is much more prone to toppling or plucking and subsequent collapse.

From an evaluation of a large number of riprap revetments along the central California coast, a number of conclusions have been reached (Fulton-Bennett and Griggs 1986):

1) Riprap revetments do not always exhibit the "flexibility" portrayed in some engineering publications. Instead of settling as a cohesive unit, individual stones tend to separate as they rotate or settle, often moving seaward in the process (figure 5).

2) Riprap walls may fail quite rapidly, often leaving behind gaps or arcuate, landslidelike scarps of oversteepened riprap or exposed fill. Because many walls are designed as low as possible to minimize costs, even minor settling can allow significant overtopping, erosion, and damage behind the wall.

3) Riprap revetments built over steep, loosely consolidated materials require carefully planned drainage systems to avoid erosion of material behind the rock. Numerous riprap walls were out-

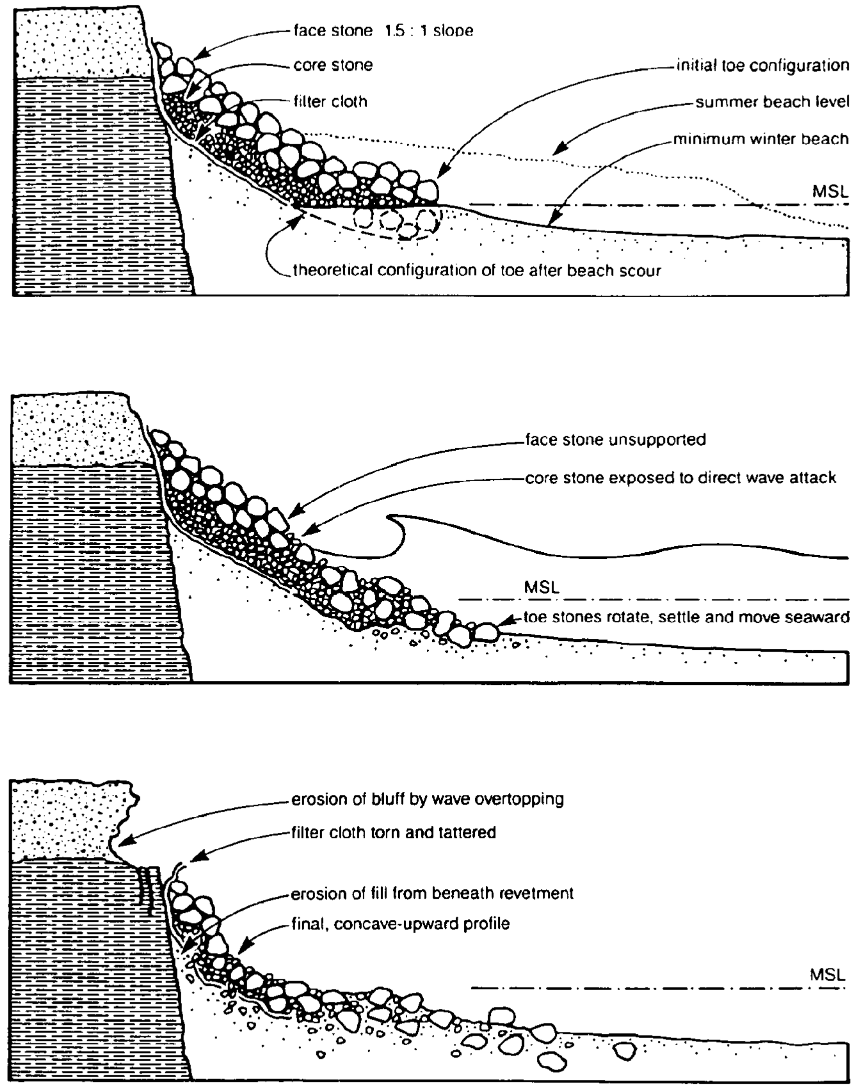


Figure 5. Failure of a riprap revetment due to scour at the toe.

flanked or partially failed because of erosion from uncontrolled runoff flowing behind or around them.

4) Although placing new rocks on top of old, settled ones is relatively simple, repairing an old riprap wall while it is being overwashed during a storm is extremely difficult and dangerous. At many sites, access is impossible under these conditions.

5) Although a riprap wall absorbs more wave energy than do impermeable seawalls, it does have a sloping seaward face. Because not all of the wave energy is absorbed under high tide and storm wave conditions, waves running up and overtopping a riprap revetment can damage houses (figure 6) or erode fill behind the riprap.

6) Where maintained and founded on bedrock, riprap has proven relatively effective in slowing erosion, but maintenance costs, even for engineered riprap, are usually quite high. The total amount of rock required in California today to protect a single ocean-front lot ranges from 500 to 2000 tons, or approximately 10 to 25 tons per foot of ocean frontage. At average prices of $35 to $45 or more per ton, these walls can cost $25,000 to $100,000. However, after a storm of roughly 10-year recurrence interval, engineered structures along the central California coast required repairs totalling 20% to 40% of their construction costs, and nonengineered structures required repairs totalling between 50% and 150% of construction costs.

Concrete Seawalls

Concrete seawalls are continuous, rigid structures whose vertical or concave faces reflect wave energy upward, downward, and back out to sea.

Figure 6. Damage to ocean front homes due to high tides and storm waves overtopping a riprap revetment during the winter of 1983 along the central California coast.

There are three major types of concrete seawalls: gravity walls, self-supported structures which balance anticipated horizontal forces by their sheer mass; cantilevered walls, which rely on support from a deep foundation; and tie-back walls, which are braced by cables or rods tied to anchors in the fill behind them. The U.S. Army Corps of Engineers (1981) lists the following as typical causes of failure for concrete seawalls fronting the Great Lakes:

a) loss of foundation support
b) inadequate penetration
c) scour at toe
d) outflanking
e) inadequate height

These causes of failure are also typical for west coast walls. Loss of fill and, therefore, support behind walls due to piping (the subsurface removal of loose sediment, soil, sand, or fill, caused by water flowing through holes or voids), gullying, or undermining are also prevalent.

Scour or undermining at the toe of a concrete seawall has been a common concern and has led to the loss of foundation support for a number of walls in the past. This has been a problem for walls founded on either sand or bedrock at the time the material is either eroded or removed. Most concrete walls studied in central California (Fulton-Bennett and Griggs 1975) toppled seaward when they failed, because of erosion of sand or bedrock at their toes, or the active pressures of fill and water behind them.

Concrete seawalls built on sandy beaches lost fill both from underneath when sand levels dropped and from behind the wall by piping. This piping takes place after fill behind the wall becomes saturated by wave splash, spray, and in some cases, groundwater. Under such saturated conditions, piping occurs because of the concentration of flow at small openings, and the resulting fluid velocities are great enough to erode granular material. Where drains or weep holes have been included within a seawall to allow for drainage from behind the wall, or where partially open joints exist between panels, it is critical that a system be used that prevents piping of sand or fill through these openings. Some combination of graded rock or gravel fill and filter cloth as well as perforated caps or plugs over the weep holes is strongly recommended in order to minimize or eliminate piping under conditions of severe wave surge and overtopping.

Concrete walls, in general, have proved to be the most durable type of protection along the central California coast. Although their initial costs may be somewhat higher than riprap and wooden walls, if they are well designed, their maintenance costs may be relatively low. Along the central California coast typical concrete seawall costs have ranged from \$750 to almost \$3000 per linear foot.

The relatively high costs of well-engineered concrete seawalls, which extend both high enough to prevent significant overtopping and deep enough so that they are not undermined by scour, have almost eliminated this type of structure from consideration by the individual homeowner. In some cases where public services, such as streets and utility lines, are involved, homeowner groups and assessment districts have cooperated with public agencies to finance and build projects of this sort. It is important to stress here the need for a continuous coherent wall or approach in contrast to individual homeowners' building a series of different types of walls. In such a situation, the entire structure is only as strong as the weakest link. Once an individual segment of a seawall is damaged or destroyed and the supporting fill begins to be removed from behind the wall, then the integrity of the entire structure is threatened.

The two most critical problems observed in concrete seawall design are preventing loss of fill from behind, around, and underneath the wall and maintaining the wall's stability and rigidity if such loss does occur (figure 7; Fulton-Bennett and Griggs 1985). Concrete walls incorporating deep (at least 8 to 10 feet below MLLW), interlocking sheet piles or panels have generally been successful in sandy areas; walls based on individual pilings and those founded in exposed bedrock have proven less durable. The latter two types have tended to lose fill or foundation support from underneath, as the sand or bedrock is removed by wave action.

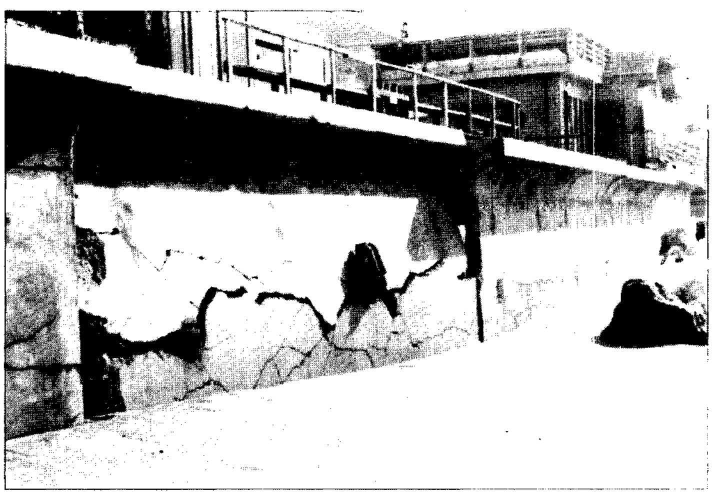


Figure 7. Loss of fill behind upper portion of seawall due to piping through weep holes. Storm wave impact against unsupported wall led to cracking and failure of portions of this just completed, thin concrete seawall.

Wooden Seawalls

Wooden seawalls are used for purposes similar to concrete seawalls and may behave as bulkheads, holding back fill materials. They also suffer many of the same problems of overtopping and undermining. They are typically cheaper to install than concrete, however, which probably accounts for their continued use.

Numerous designs for wood walls have been tried over the years, including the use of railroad ties and steel H-piles as vertical supports. The most common design along the central California coast incorporates vertical wooden pilings six to eight feet apart, embedded in the sand with horizontal boards (called lagging), usually 3 x 12 to 6 x 12 inches in cross-section, nailed or bolted to the landward side of the pilings. In the last decade, such walls have also incorporated filter cloth behind the horizontal wood planks, and often tiebacks into the fill behind the wall.

Even chemically treated wooden walls tend to decay and deteriorate with exposure to salt water. No matter how well designed, most wooden walls will usually decay after 10 to 20 years in the surf zone. Wooden walls are also highly vulnerable to battering by floating logs and debris, which is common along the northern California and Oregon coasts (Griggs 1987b). Riprap placed in front of a wooden wall may reduce this problem at low tide or under moderate wave conditions, but this battering problem has proven to be a difficult one to avoid under severe wave attack (figures 8 and 9).

Damage to many wooden walls has been initiated when floating debris (typically large logs) cracked or broke horizontal planks or the pilings themselves, allowing fill to be removed at these points (figure 10), despite the presence of filter cloth. Piping has also been a problem when timber walls are overtopped. Once the fill begins to erode from behind a wooden wall, the uppermost planks are almost immediately separated from the pilings by waves, either because bolts or nails are pulled out, or (more commonly) the boards are splintered by wave forces. This allows additional overtopping to erode fill on either side of the damaged area, causing gullying behind the wall (figure 11). However, where wooden walls are fronted by riprap, even though some fill may erode, the planks often stay in place at levels below the top of the riprap. One significant improvement in the construction of timber seawalls in recent years at some sites has been the use of Epoxy-coated steel H-piles (which constrain the

Figure 8. Storm waves carrying logs and debris overtopping a low wooden seawall in northern Monterey Bay during the winter of 1983.

lagging, in contrast to simply using wood piles) and 6-inch-thick timber lagging. Walls of this construction have proved to be far more able to withstand the wave and debris impact than the piling walls.

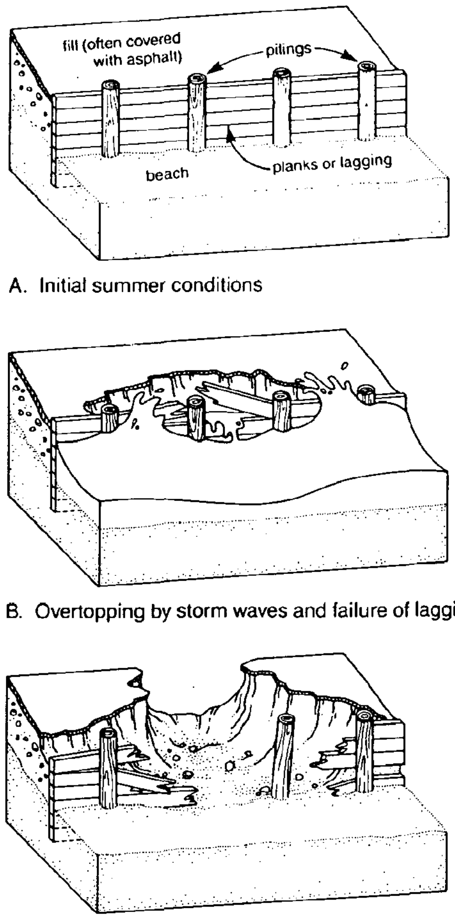
Figure 9. Wooden seawall from figure 8 following storm wave attack. Approxi-mately 700 feet of seawall was destroyed as the lagging was battered by logs and fill was lost. This $1.5 million wall had been completed just two months before.

Discussion

All shoreline protection structures must be engineered and built to withstand four basic types of wave effects: overtopping, undermining, outflanking, and impact.

Overtopping is defined as the transport of significant quantities of ocean water over the top of a seawall as green water, splash, or spray. Overtopping causes damage in several ways, by exerting direct vertical and horizontal forces and by eroding material from behind walls. In most coastal environments it is not practical to build a seawall that will not be overtopped during severe storm conditions. At many sites, cost is a limiting factor. In addition, few coastal residents or cities are willing to build seawalls which will significantly block their view of the ocean. Standard run-up calculations for seawalls typically consider only the frequency of overtopping by green water. The height of this run-up is usually calculated using empirical or theoretical formulae based on water depth, beach slope, significant wave height, wave period, and maximum expected sea level (which continues to change). Variabilities in the natural environment, however, can produce a wide range in the maximum wave run-up elevations calculated using this method.

Undermining of seawalls occurs when foundation materials (usually sand, fill, or rock) are removed by wave action. This may take place not only when beach sand is scoured or fluidized, but also where bedrock erodes rapidly during storms.



A. Initial summer conditions

B. Overtopping by storm waves and failure of lagging

C. Failure of wall and loss of fill

Figure 10. Progressive failure of a wooden seawall through overtopping and loss of fill.

In either case, the result of undermining is often rapid loss of fill from behind a wall, and in some cases, structural failure. Predicting the level to which a beach may be scoured is a difficult task. Coastal engineers have used a variety of "scour depths" in designing seawalls. Since there are no widely accepted formulas for calculating these depths, estimates based on field observations made during or (more commonly) after storms are used. In areas where bedrock is deep, borings are often used to determine the depth of storm lag deposits, consisting of gravel and cobbles. However, several such layers may be encountered, and in the absence of accurate dating methods, the selection of a design or expected scour depth can be quite uncertain.

The depth to which scour occurs will depend heavily on how far landward or seaward a structure is located on the beach profile. Within this zone, the depth of beach scour and liquefaction should increase rapidly with increasing distance seaward. Thus, there is an inherent problem in any solution that involves moving a structure seaward: the amount of energy it receives and the effects of that energy will be greatly increased.

Outflanking occurs when material to either side of a seawall erodes to a point where it

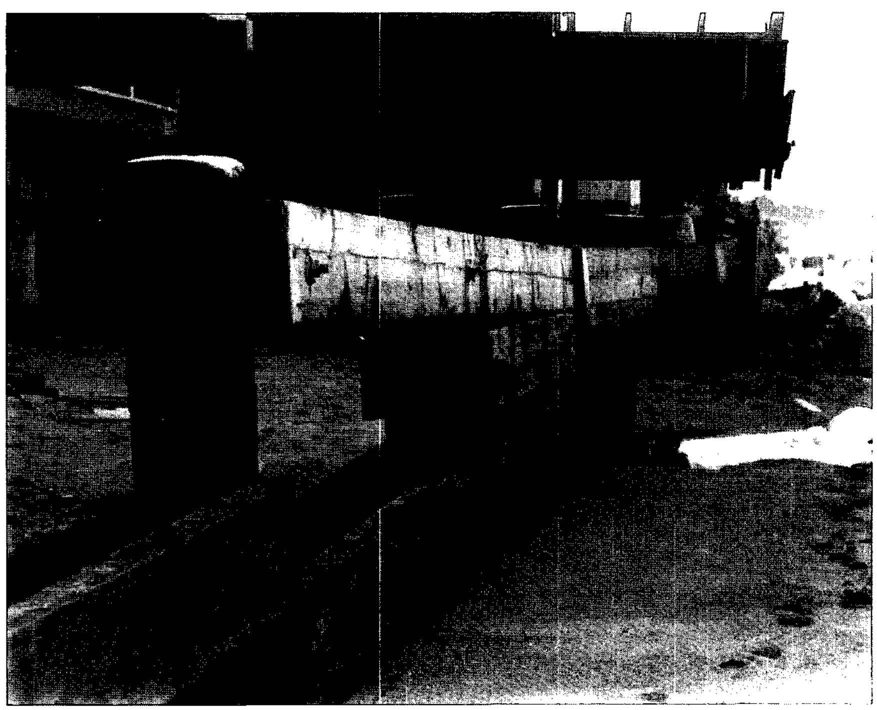


Figure 11. Loss of fill behind a wooden seawall due to overtopping and undermining.

threatens or damages the wall itself, or the property behind it. Along a progressively eroding coast, all successful, isolated protection structures will be gradually outflanked because the coastline on either side will erode more rapidly than that behind the wall. This is a relatively predictable process and should be planned for in the design of any isolated wall in a rapidly eroding area. Most often, it is taken into account through the use of wing walls running landward from the ends of the main structure. However, because of high costs and practical difficulties, such future outflanking is usually ignored until it causes property damage (figure 12).

Often, outflanking of one wall leads to the construction of additional walls adjacent to the first. As the amount of continuously protected coastline increases, outflanking becomes a problem in the unprotected gaps. Nonetheless, both for isolated walls and for gaps in protected coastlines, the question must be asked: Do sea walls increase erosion in adjacent areas?

A recent four-year study along the central California coast was directed at documenting the effects of coastal protection structures (seawalls and riprap revetments) on beaches (Griggs and Tait 1988; Tait and Griggs 1990). A number of temporary or seasonal effects of seawalls on the fronting and adjacent beaches were documented in this field work. A zone of increased scour or erosion was often observed downcoast from the seawalls studied, and the extent of this erosion appeared to be related to several factors—the configuration of the wing wall and its reflectivity, the angle of wave approach, and the height and period of the waves. Waves were commonly observed reflecting off the wing walls and were capable in one case of producing increased scour up to 300 to 400 feet downcoast.

Conclusions

Of the three major types of protection, concrete walls generally have been most successful in reducing erosion and property damage and have been the most durable, over the long term. However, to survive, concrete walls supported on discrete pilings have required moderate to high maintenance in the form of riprap toe protection. Riprap walls have fared less well than concrete walls, but better than wooden walls. However, their maintenance costs have often been much higher than anticipated, particularly where placed on deep sand beaches. Wooden walls have proven to be least successful in preventing erosion and damage, and most are easily damaged by logs and debris during severe storms. Wooden walls fronted entirely by riprap have been more successful, as long as the riprap does not settle.

Figure 12. Riprap has been outflanked, leading to erosion of unprotected property as well as bluff behind riprap.

On the whole, few protective structures along the central California coast have stood the long-term tests of time, surviving unassisted and preventing damage and erosion for more than 20 years or longer than their design life. Many structures have become structurally unsound, required considerable maintenance or repair, or failed to adequately reduce property damage for more than one severe storm period. Thus, the effective lifetime of a structure often depends on how many mild winters pass before the next severe storm. However, most of the structures have reduced erosion rates, at least over the short term.

There are a number of options—some structural, some nonstructural—available for people with threatened property. Before any protective structure is designed and built, its initial costs, its maintenance costs, its probable lifespan, its technical merits and limitations, and all of its potential impacts on the adjacent coastline need to be fully considered.

References

Fulton-Bennett, K.W., and Griggs, G.B., 1986. Coastal protection structures and their effectiveness. Joint publication of the State of California, Department of Boating and Waterways and the Institute of Marine Sciences, University of California, Santa Cruz.

Griggs, G.B., 1986. Relocation or reconstruction: viable approaches for structures in areas of high coastal erosion. Shore and Beach 54: 8-16.

Griggs, G.B., 1987a. California's shoreline erosion: the state of the problem. Proc. Coastal Zone '87, Seattle, WA., Am. Soc. Civil Engin. pp. 1370-1383.

Griggs, G.B., 1987b. Failure of coastal protection at Seacliff State Beach, Santa Cruz County, California. Envir. Manag. 11:175-182.

Griggs, G.B., and Fulton-Bennett, K.W., 1988. Rip rap revetments and seawalls and their effectiveness along the central coast of California, Shore and Beach 56:3-11.

Griggs, G.B., Pepper, J. and Jordan, M.E., 1991. California's coastal hazards: a critical look at existing land use policies and practices. In: The California Coastal Experience, Am.Soc. Civil.Engin.: 89-107.

Griggs, G.B. and Tait, J.F., 1988. The effects of coastal protection structures on beaches along northern Monterey Bay, California, Jour. Coastal Research Spec. Issue No. 4: 93-111.

Griggs, G.B. and Savoy, L.E., 1985. Living with the California coast. Duke University Press, Durham, NC.

Leonard, L., Clayton, T., Dixon, K. and Pilkey, O.H. , 1989. U.S. beach replenishment experience: a comparison of the Atlantic, Pacific, and Gulf coasts. Proc. Coastal Zone '89, Amer. Soc. Civil Engin.

Moffatt and Nichol, Engineers, 1983. Construction materials for coastal structures. U.S. Army Corps of Engineers,Coastal Engineering Research Center Special Report No. 10.

Tait, J.F. and Griggs, G.B., 1990. Beach response to the presence of a seawall: a comparison of observations, Shore and Beach 58:11-28.

U.S. Army Corps of Engineers, 1977. Coastal Engineering Research Center, Shore Protection Manual, V. 1 and 2, 3rd edition.

U.S. Army Corps of Engineers, 1981. Low Cost Shore Protection—A Guide for Engineers and Contractors, Vicksburg, MS.

SHORE PROTECTION AND ENGINEERING: A LOCAL PERSPECTIVE

Matt Spangler
Lincoln County Department of Planning and Development

Shore protection and engineering issues present a number of challenges for local planners and other regulatory officials. This brief discussion focuses on shore protection issues encountered in the context of the local land use and regulatory process in the State of Oregon. Primary emphasis is on the identification of policy questions to be addressed in developing a comprehensive approach to shore protection management.

Planning vs. Engineering

In their paper, Nicholas Kraus and William McDougal advance the principle of "plan regionally, engineer locally" as a key to proper management of shoe protection. Unfortunately, this sound concept has seen little application in Oregon. Shore protection projects are typically planned on a single-purpose basis, and current policy and regulatory requirements neither require nor encourage the integration of these projects into a regional context. The result is essentially no consideration of regional impacts (for example, the effects on a littoral cell) in the regulatory review of individual projects.

The Relationship between Shore Retention and Backland Protection

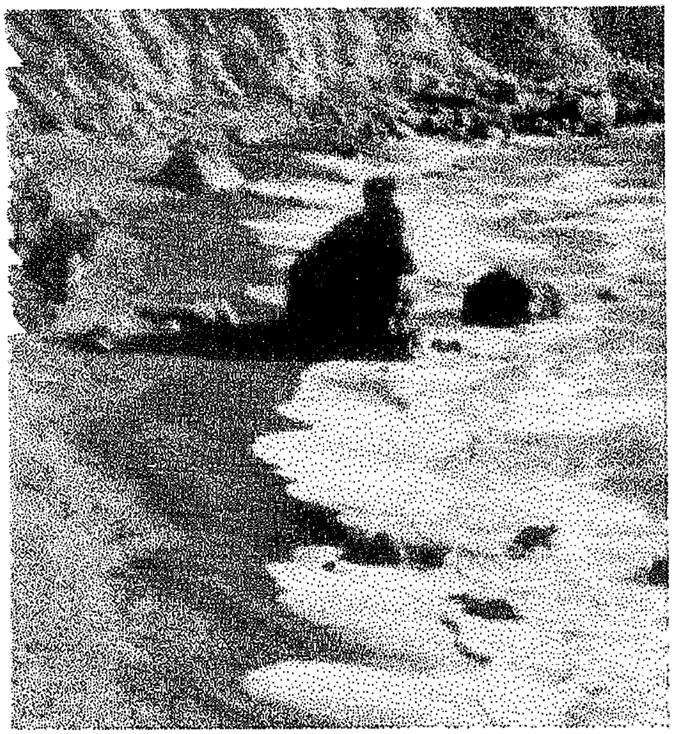
Kraus and McDougal discuss the distinction between shore retention and backland protection, separate concepts contained within the generic term "shore protection." Oregon shore protection efforts have focused almost exclusively on backland protection primarily through various structural means. Virtually no attention had been paid to the role of beach stabilization in addressing problems associated with shoreline recession. The importance of an integrated approach to shore protection, including consideration of both shore retention and backland protection in the context of structural and nonstructural techniques of protection, is a largely overlooked policy consideration.

Kraus and McDougal go on to point out the importance of integrating the various options in shore protection techniques with the concept of sand supply management on a littoral cell basis. While existing policy expresses preferences for nonstructural means of protection and attempts to limit the placement of hard structures, it fails to make any connection between these limitations and the objective of overall sand supply management within the littoral cell.

Toward a Management System for Shore Protection

The development of a coherent management system for shore protection must begin with a clear articulation of the goals and objectives of such a management system. While it is clear that known technical data on littoral cell dynamics must be factored in to the development of any management objectives, perhaps a more important first step is the formulation of overall goals for the management of our public beaches. Only by knowing and clearly stating these goals can we appropriately use our technical knowledge as a base for devising a coherent management program.

Once an overall policy framework is established, specific management priorities need to be developed on a subregional (or littoral cell) basis. Many factors, including existing development patterns, will influence to what extent and with which management tools the overall goals can be achieved. By developing overall policy objectives and then formulating implementation strategies on the local level, we can put into practice the admonition to "plan regionally, engineer locally."



PUBLIC POLICY

Recent Legal Developments in Coastal Natural Hazards Policy

Richard G. Hildreth
University of Oregon Ocean and Coastal Law Center

Introduction

Coastal areas of the United States are affected by a wide range of natural hazards that threaten lives and property. Those hazards include severe storms, floods, erosion, landslides, earthquakes, tsunamis, and subsidence. Over the past decade the problem of coastal hazards has become more pressing. Americans continue to demand more opportunities for coastal recreation, leading to pressure to develop resort areas and single-family homes along the beach. The consequences of this development are increased exposure to storms and the potential for loss of life and property, as was vividly demonstrated in South Carolina when Hurricane Hugo hit two years ago.

Another problem, although less dramatic, is the interference of development with natural shoreline processes. Erosion control structures, such as seawalls and bulkheads, have the ironic effect of accelerating erosion, either in front of the development the structure is designed to protect, or downdrift. In addition, these structures inhibit the ability of the beach to absorb storm energy, thus exposing structures to the full force of wind and waves.

However, decision makers in the private and public sectors should avoid basing policies on preconceptions regarding typical shorelines and their state of development. Establishing setbacks for new development, relocating endangered structures, providing beach nourishment, building protective structures, or doing nothing may each be appropriate under specific local conditions.

State Responses Around the U.S.

Currently, 13 states have some form of setback requirement for coastal development. Many states also have laws to protect dunes, which are the first line of defense from storms (Maine 1987).

Following are some examples of innovative efforts to address coastal hazards (NOAA OCRM 1990).

(1) North Carolina has established setback lines in areas of designated ocean hazard to protect buildings from coastal storms. The setback lines will ensure at least 60 years of protection from coastal erosion for large structures and 30 years of protection for residential structures. Building infrastructures that would serve ocean-hazard areas—such as roads, bridges, water and sewer lines, and erosion-control structures—is allowed only if the structures will be reasonably safe from coastal hazards and will not promote additional development in hazardous areas. The state also provides hazard notices to all permit applicants. The notices give the erosion rate in the area, note that bulkheads and seawalls are not allowed, and warn that the area is hazardous and the property owner is at risk.

(2) South Carolina's 1988 Beachfront Management Act provides a comprehensive approach for managing the state's beach and dune system. The act requires the South Carolina Coastal Council to determine local erosion rates for all portions of the coast, except areas already protected from development, and to establish development setbacks derived from expected beach erosion over 40 years. To help preserve the beach and ensure that the act's 40-year retreat goal was realized, the act prohibits all new erosion-control structures and requires that such structures damaged more than 50% be removed. The act also requires the disclosure of specific hazardous conditions during property transfers.

In September 1989, Hurricane Hugo provided a severe test of the Beachfront Management Act. Since the hurricane struck, the state has faced political and legal pressures regarding the implications of the act for reconstruction and repair of structures along the state's coast. After intense debate over the future of beach management in South Carolina, the act was amended in June 1990. The most significant changes are (1) strengthened prohibitions against erosion control structures by forbidding the construction of all erosion control devices, not just vertical structures, and (2) authority for the council to issue a special permit when its restriction on development would render a lot unbuildable (owners are required to remove the structure if it becomes situated on the active beach through erosion processes). Enforcement of the act has received strong support from the South Carolina Supreme Court, as I will discuss later.

(3) The Rhode Island Coastal Resources Management Council has mapped critical erosion areas and calculated average annual erosion rates for those areas. The state uses the information to establish building setback lines in areas of intense erosion. Additionally, the council has adopted a poststorm policy which authorizes a moratorium of up to 30 days on reconstruction of structures in specific zones at least 50% destroyed by storm, flood, wave, and wind damage. During the moratorium, the state may consider purchasing damaged properties or pursue other mitigation responses.

(4) In July 1989 the Michigan State Legislature amended the state's Sand Dunes Protection and Management Act to grant the state Department of Natural Resources authority to regulate activities within newly defined "Critical Dune Areas." Key provisions of the act include the designation of 70,000 acres of Critical Dune Areas, the establishment of a model zoning plan for the protection of sand dunes, and an option for local governments to administer the act. The amendments prohibit certain uses in Critical Dune Areas unless the administering authority grants a variance.

(5) Using the results of a recent study, the Massachusetts Coastal Zone Management Program has developed policies that require a review of projects proposed in the 100-year floodplain to determine the effects of relative sea level rise as well as the project's potential to exacerbate those effects.

(6) In California the San Francisco Bay Conservation and Development Commission has taken a leadership role in planning for the effects of possible future rises in sea level. In 1989 the commission developed new policies to require that new shoreline development take sea level rise into consideration. These policies generally require that any new project requiring fill should be above the highest estimated tide level for the design life of the development. The commission also has been working with Bay Area local governments to assist them in addressing future sea level rise.

(7) The Delaware Coastal Management Program has prepared a report which assesses management alternatives to address shoreline erosion along Delaware's Atlantic coast over the next decade. The report concluded that a policy of retreat from the coast was the only viable long-term option, but also proposed a short-term action plan, since implemented, to renourish beaches where economically justified.

(8) In June 1989 the Hawaii Coastal Zone Management Program completed the "Hawaii Shoreline Erosion Management Study," which provided a comprehensive review of erosion management in Hawaii. This was a critical step toward developing consistent regulations governing the use of structural and nonstructural measures to control erosion. The study recommended that the Hawaii coastal program take the lead in working with county governments to develop local long-term plans for managing erosion in erosion-prone areas.

(9) In the Australian states of Victoria and Tasmania, local governments have factored into their coastal development decisions the possibility of sea level rise. Up and down Australia's extensive coastlines, structural responses to coastal erosion are being reduced in favor of renourishment of heavily used beaches, combined with dune restoration and protection programs. Officials are stringently reviewing coastal sand-mining practices and policies. The Australian federal and Queensland state governments plan to jointly nominate Fraser Island, the world's largest sand island, to the World Heritage conservation list in order to preserve it for future generations.

Federal Responses in the U.S.

In Washington, D.C., Congress continues to wrestle with the legal and policy aspects of coastal hazards management. For example, the proposed National Flood Insurance, Mitigation, and Erosion Management Act of 1991 would phase out federal flood insurance coverage for existing development and prohibit such insurance for new development in designated erosion-prone coastal areas.

Under the Coastal Barrier Improvement Act of 1990, the United States Fish and Wildlife Service is required to map all areas along the Pacific coast, except Alaska, that might qualify for addition to the federal Coastal Barrier Resources System established on the Atlantic and Gulf coasts under legislation enacted in 1982. That legislation prohibits any form of federal assistance, including federal flood insurance in coastal areas designated as part of the coastal barrier system. Under the 1990 amendments, the Interior Department will recommend to Congress those Pacific coast areas that state governors deem are appropriate for inclusion in the federal coastal barrier system. Eldon Hout and Paul Klarin of the Oregon Department of Land Conservation and Development (DLCD) are working closely with the Fish and Wildlife Service in an attempt to avoid the many mapping errors that occurred in the Interior Department's earlier effort to map Oregon coastal barriers.

Building on the federal model, Maine's coastal program has developed a state Coastal Barriers Resource System. State expenditures for development activities within the Maine coastal barrier system are prohibited. Depending on the outcome of the federal process regarding Oregon coastal barriers, Oregon might want to establish a state coastal barrier system like Maine's.

Section 309 of the federal Coastal Zone Management Act Amendments of 1990 established a new federal grant program to encourage coastal states like Oregon to improve their federally approved coastal zone management programs in several areas, including the management of coastal natural hazards. The clear thrust of section 309 is toward further "preventing or significantly reducing threats to life and destruction of property by eliminating development and redevelopment in high-hazard areas . . . and anticipating and managing the affects of potential sea level rise." As Oregon's coastal zone management agency, DLCD could seek 309 funds for what I believe would be a very timely review of the legal and policy framework for coastal natural hazards management in Oregon. Those components include goals 7, 17, and 18 of the statewide land-use planning program; the Removal-Fill law (ORS 196.800-.990), administered by the Division of State Lands; and the Shoreline Construction law (ORS 390.605-.770), administered by the Parks and Recreation Division of the Department of Transportation.

As my summary of recent state and federal legislative developments indicates, Oregon would not be alone in taking a hard look at its coastal hazards laws and policies during the 1990s.

Judicial Support for State and Local Hazards Management

Certainly many of the state coastal hazard programs I have just described have resulted in increased restrictions on coastal development. The validity of some of those restrictions has been challenged in the state and federal courts. In preparing this paper I have done an extensive survey of relevant state and federal court decisions and can report to you that almost uniformly the courts have supported the enforcement of development restrictions based on credible scientific evidence of a hazard to life or property (Mack 1983; Town 1991). In the extreme situation where property is rendered undevelopable by serious hazards, they have supported the enforcement of such restrictions without requiring compensation to the affected landowner.

Indicative of this trend of strong judicial support is a series of decisions rendered by the South Carolina Supreme Court (Beard 1991; Lucas 1991) upholding the restrictions of South Carolina's Beachfront Management Act on reconstruction of properties damaged by Hurricane Hugo (Beatley 1990). The South Carolina Supreme Court is probably as supportive of private property rights as any state court in the nation. Yet the court has upheld stringent enforcement of the South Carolina act's restrictions on reconstruction in hazardous locations without compensation to the affected landowners, finding that the well-documented public harms that flow from development in hazardous locations justify such regulation (Carter 1984). A federal court of appeals just below the U.S. Supreme Court also has upheld the validity of the South Carolina act (Esposito 1991).

These decisions regarding the South Carolina act join recent court decisions regarding similar legislation in Florida and elsewhere which also have found that regulations strictly controlling development in hazardous coastal areas may be enforced without compensation (Arrington 1989; McNulty 1989; Rolleston 1980; Town 1981).

The lesson to be derived from these opinions seems to be that where the legislature makes specific findings regarding the risks posed by coastal natural hazards and sets forth policies to reduce or avoid those risks, the courts generally will support enforcement of those policies (Comment 1991; Hwang 1991; Kusler 1989; Pendergrast 1984; Pfundstein and Charles 1991).

The trend in the coastal hazards decisions just described is further supported by a recent California decision regarding inland flood hazards (First English 1989). That decision upheld a Los Angeles County moratorium on redevelopment in a flood-prone creek pending study of the safety issues involved against a challenge that property affected by the moratorium was being unconstitutionally taken without compensation. This case had been sent back to the California court by the U. S. Supreme Court after it rendered its famous decision in the *First English Evangelical* case, which ruled that if local governments did regulate private property unconstitutionally, they could not merely repeal the offending regulation but also must pay compensation for any damages suffered by the regulated property owner due to the regulation.

That basic principle continues to apply to coastal hazards regulation as well. However, the resulting California court decision and the coastal hazards decisions seem to stand for a very important point: that when a coastal hazards regulation is based on credible scientific evidence, the courts are very unlikely to hold that the regulating governmental entity has regulated property unconstitutionally. Regulations based on inadequate evidence or on poorly documented evidence of course remain vulnerable to judicial invalidation (Annicelli 1983; Saint Joe Paper 1988).

At this time it seems appropriate to assess the current state of knowledge regarding natural hazards on the Oregon coast and the risks they pose to life and property, both public and private. Flowing from that assessment could be an evaluation of the adequacy of current Oregon regulatory and planning processes to reduce or avoid those risks.

Relevant Oregon court decisions seem to fall in line with the general trend I have previously outlined. The Oregon courts have supported protection of public access to the state's sandy beaches through stringent state regulation of construction on private property seaward of the coastal vegetation line (State Highway Commission 1971). A recent request to build a seawall on the beach at Cannon Beach was rejected by state and local agencies; the rejections were then upheld at the trial court level. These actions fall in line with the general pattern in Oregon courts. Any appellate court decision resulting from that particular matter would obviously be an important indicator of future directions in the Oregon courts with respect to the control of shoreline construction for reasons of natural hazards as well as public access.

Accommodating Public and Private Interests in Coastal Hazards Management

As I have said, the courts generally support enforcement of coastal hazards regulations without compensation to affected landowners. However, that does not mean that some form of compensation may not be provided even though it is not constitutionally required. Throughout the nation and in Oregon we need to give more thought to schemes that recognize the sometimes dramatic impacts of nature on coastal property owners and that attempt to accommodate affected private interests wherever possible. Techniques for achieving such accommodation include (1) acquiring outright fee simple or less than fee simple interests such as conservation easements in affected coastal properties, (2) reducing property tax values and rates, and (3) awarding density bonuses and transferrable development rights to affected property owners.

I understand that in coastal Oregon some local governments have provided for density bonuses to be awarded to developers who avoid hazardous areas. Their experiences need to be documented. Ideally such accommodations should be worked out at the local level.

In that connection, I recently heard a consultant's presentation on the development of a local wetlands conservation plan for Rockaway Beach. The process was moving forward with extensive local participation. The consultant acknowledged that there clearly would be some winners and losers locally in the designation of wetlands on privately owned property and in the community decision making about their future. Wetlands conservation has reached the highest political levels in this nation, and local wetland owners are faced with a great deal of uncertainty and a period of rapid change in federal and state laws, policies, and court decisions. However, what impressed me was that it appeared there would at least be some local winners in the Rockaway Beach process. Without such a local effort, wetland owners in Rockaway Beach might only be losers in trying to deal with the rapidly changing complexities of federal and state wetland law and policy.

Implications for Oregon Coastal Hazards Management

We know a lot more about coastal processes and coastal engineering and their effects and limitations than we did when Oregon put in place its current scheme for coastal natural hazards management. The time may be right to review that scheme and, where appropriate, revise it through legislative action, administrative rule making, comprehensive plan revisions, and related processes. Furthermore, some federal dollars may be available to assist in that effort.

Following are some questions that need to be reexamined:

(1) Are structural protection devices always bad for the adjacent beach and neighboring properties, or is that an overgeneralization?

(2) Should alteration of dunes for view preservation and similar purposes continue to be authorized by goal 18?

(3) Are the true and total costs, both direct and indirect, of coastal development and coastal protection works currently being fairly allocated?

Oregon's current approaches to coastal hazards need revision regardless of whether the Oregon coast will or will not be significantly affected by any sea level rise caused by global warming. And if at some point in the future, officials and scientists reach the consensus that accelerated sea level rise poses risks to Oregon, the state's revised coastal hazards program will certainly be the starting point for designing and implementing adaptive responses (Corfield 1987; Rychlak 1990; Titus 1991, 1990).

In conclusion, and in a more philosophical vain, I believe three emerging international principles governing resources development (morally but not legally binding at this point) are relevant to revisions in Oregon hazards law and policy:

(1) the "polluter pays" principle—the notion that any development allowed in hazardous coastal areas should pay its full costs;

(2) the precautionary principle—the notion that in the absence of good information about a coastal development's safety and impacts on adjacent beaches and neighboring properties, we don't move forward with it until we have better information; and

(3) the principle favoring sustainable development of resources over unsustainable development—building in hazardous coastal locations generally is not a sustainable use of those resources.

References

Annicelli v. Town of South Kingstown, 463 A.2d 133 (R.I. Sup. Ct. 1983).

Arrington v. Mattox, 767 S.W.2d 957 (Tex. Ct. App. 1989).

Beard v. S.C. Coastal Council, 403 S.E.2d 620 (S.C. Sup. Ct. 1991).

Beatley, Managing Reconstruction Along the South Carolina Coast (U. of Colorado 1990).

Carter v. S.C. Coastal Council, 404 S.E.2d 895 (S.C. Sup. Ct. 1984).

Coastal Barrier Improvement Act of 1990.

Coastal Zone Management Act Amendments of 1990, section 309 (16 U.S.C. § 1456b).

Comment, Shifting Sands and Shifting Doctrines, 79 California Law Review 205 (1991).

Corfield, Sand Rights: Using California's Public Trust Doctrine to Protect Against Coastal Erosion, 24 San Diego L. Rev. 727 (1987).

Esposito v. S.C. Coastal Council, 60 U.S. Law Week 2065 (4th Cir. 1991).

First English Evangelical v. County of Los Angeles, 210 Cal. App. 3d 1353, 258 Cal. Rptr. 893 (1989).

Hwang, Shoreline Setback Regulations and the Takings Analysis, 13 Hawaii L. Rev. 1 (1991).

Kusler, Avoiding Public Liability in Floodplain Management (Association of State Floodplain Managers 1989).

Lucas v. S.C. Coastal Council, 404 S.E.2d 895 (S.C. Sup. Ct. 1991).

Mack v. Town of Cape Elizabeth, 463 A.2d 717 (Me. Sup. Ct. 1983).

Maine Department of Environmental Protection Dune Rule 355 (1987).

McNulty v. Town of Indialantic, 727 F. Supp. 604 (M.D. Fla. 1989).

NOAA OCRM, Coastal Management Solutions to Natural Hazards (Technical Assistance Bulletin #103, 1990).

Pendergrast, The Georgia Shore Assistance Act, 17 Natural Resources Law 397 (1984).

Proposed National Flood Insurance, Mitigation, and Erosion Management Act of 1991 (H.R. 1236, S. 1650).

Pfundstein & Charles, Florida's Coastal Construction Regulations and the Taking Issue: The Complexities of Drawing Lines in the Sand, 6 J. Land Use & Envtl. Law 255 (1991).

Rolleston v. State, 266 S.E.2d 189 (Ga. Sup. Ct. 1980).

Rychlak, Thermal Expansion, Melting Glaciers, Rising Tides: The Public Trust in Mississippi, 11 Mississippi College Law Review 1 (1990).

Saint Joe Paper v. Department of Natural Resources, 536 So. 2d 1119 (Fla. Ct. App. 1988).

State Highway Commission v. Fultz, 261 Or. 289, 491 P.2d 1171 (1971).

Titus, Greenhouse Effect and Coastal Wetland Policy, 15 Envtl. Mgmt. No. 1 at 39 (1991).

Titus, Strategies for Adapting to the Greenhouse Effect, APA Journal Summer 1990 at 311.

Town of Indialantic v. McNulty, 400 So.2d 1227 (Fla. Ct. App. 1981).

Town of Palm Beach v. Department of Natural Resources, 577 So. 2d 1383 (Fla. Ct. App. 1991).

PUBLIC POLICY

COASTAL HAZARDS POLICY ISSUES ON THE WEST COAST

CALIFORNIA'S COASTAL HAZARDS POLICIES: A CRITIQUE

Gary B. Griggs
Department of Earth Sciences, University of California, Santa Cruz
James E. Pepper
Department of Environmental Studies, University of California, Santa Cruz
Martha E. Jordan
Santa Cruz County Planning Department

Introduction

In adopting the 1972 California Coastal Initiative, the public set a new statewide direction in coastal land use. Seeking to reverse the incremental, piecemeal, sprawling pattern of development that had already overrun many coastal areas and degraded the quality of the contiguous public trust lands, the people were unequivocal regarding the primacy of coastal protection, declaring: "The permanent protection of the remaining natural and scenic resources of the coastal zone is a paramount concern to present and future residents of the State and nation" (State of California 1972).

The California Coastal Zone Conservation Commission (hereinafter referred to as the Coastal Commission) was created through this citizen initiative and was charged with the preparation of a Coastal Plan for subsequent legislative approval. This plan, completed in 1975, was designed to achieve two objectives: "(1) protect the California coast as a great natural resource for the benefit of present and future generations; and (2) use the coast to meet human needs in a manner that protects the irreplaceable resources of coastal lands and waters" (Coastal Commission 1975). Among the major findings and recommendations was a policy statement formulated to provide protection against natural hazards:

> Development along the coast of California is threatened by a number of natural hazards such as floods, earthquakes, landslides, cliff erosion, and tidal waves (tsunami waves). The Plan proposes policies to restrict new development in floodplains, require that a geologic hazards description be made a part of residential sales information, place limitations on uses of land within coastal areas of highest risk, prevent public subsidies for hazardous development, and provide setbacks from erosion-prone bluffs. (Coastal Commission 1975)

A related recommendation concerned safeguarding against the harmful effects of seawalls, breakwaters, and other shoreline structures:

> Seawalls, breakwaters, groins, and other structures near the shoreline can detract from the scenic appearance of the oceanfront and can affect the supply of beach sand. The plan limits the construction of shoreline structures to those necessary to protect existing buildings and public facilities, and for beach protection and restoration. Special design consideration is proposed to insure continued sand supply to beaches, to provide for public access, and to minimize the visual impact of structures. (Coastal Commission 1975)

This paper reports on the results of these and other coastal hazard policy recommendations forwarded to the State Legislature by the Coastal Commission. Three major problem areas are addressed: (1) limitations on hazard identification and evaluation; (2) hazard liability issues; and (3) variation and effectiveness in policies and practices governing (a) blufftop and beach-level development, (b) emergency conditions and reconstruction, and (c) emplacement of coastal protection structures.

*Reprinted, with permission of the publisher, from *The California Coastal Zone Experience*, 1991, T.H. Wakeman and G.W. Domurat, eds., Long Beach, CA: American Society of Civil Engineers, pp. 89-107.

Background

Human Adaptations and Responses to Coastal Hazards

The range of human responses and adaptations to natural hazards varies widely. Burton identified major modes of coping with natural hazards: (1) loss absorption, (2) hazard acceptance, (3) hazard reduction, and (4) change in use and livelihood in hazard areas (Burton et al 1978). These modes generally occur sequentially over time, reflecting movement across discernible threshold levels—hazard awareness, action, and intolerance.

The extent to which a society or community remains unaffected by natural processes is its absorptive capacity. When adverse changes are recognized as losses, but remain tolerated, a pattern of loss acceptance develops as the inhabitants learn to accept the costs of living in a hazard prone environment. When people reach the limits of loss acceptance, they attempt to control the force of the natural hazard, and thus reduce their vulnerability to the loss of property and life. If loss reduction ultimately proves to be ineffective or too costly, substantial changes in the types of land uses or the relocation of uses from hazardous areas becomes an important alternative in the choice of response and adaptation.

The lowest cost and potentially highest risk approach to coastal hazard mitigation is to do nothing. Depending upon the particular location—its setback from the sea, elevation of the structure, past erosion or inundation problems—this approach may work for a limited period of time. There is no cost until a major storm finally does occur, and then either a rapid emergency response is necessary or losses may be very high.

Relocation of oceanfront structures or utilities is a second option. Where a parcel is large enough, a threatened structure can be moved landward on the same parcel to extend the period of protection, depending upon average erosion rates. In many cases this will not be possible and relocation will require acquisition of a separate lot. Recent examples of comparative costs of relocation or reconstruction versus protection have indicated that in the long run, relocation is far less expensive (Griggs 1986), although it is likely that this option is not often seriously considered by most threatened oceanfront property owners simply because of a desire to protect their ocean view at any cost.

Historically, the third and most common approach to protecting private or public structures or utilities from coastal hazards has been the construction of some type of "hard" protective structure. Protective devices can vary considerably in type, size, effectiveness, and life span (Fulton-Bennett and Griggs 1986). The purpose of any hard structure, regardless of type, is essentially the same: reduce or halt the adverse impacts of wave attack and shoreline erosion and thereby protect threatened structures and property.

A fourth option, beach nourishment or replenishment, has emerged as an appealing "soft" approach to dealing with the problems of shoreline erosion in sandy beach environments. On the surface this strategy presents an attractive compromise to the extremes of abandoning the shoreline or armoring it with concrete or rock. The beach is nourished or replenished with sand, from either an offshore or inland source, to increase the width of the beach such that it serves as a more effective buffer and protects the shoreline from wave attack, thereby reducing erosion. However, the economics of a large-scale beach nourishment program and the distribution of costs pose serious questions for this approach to coastal protection.

In terms of minimizing economic costs and environmental impacts, a fifth option—coastal hazard avoidance, ranks highest. Not only are the public costs associated with disaster relief, construction of protective devices, and government assistance insurance reduced or eliminated, so too are the adverse environmental effects of coastal protection structures on contiguous public trust lands. The principal limitation of the hazard avoidance strategy is the political cost associated with the denial of private development in high risk areas. The mechanisms available for a hazard-avoidance strategy are land use planning and regulation or public purchase of property rights in high risk areas through easements, life estates, or fee-simple ownership.

California Population Growth and Concentration

Coastal hazards are a function of the presence of human beings and their myriad activities in interaction with naturally occurring coastal processes. With the exception of changes due to coastal erosion, the coastline has the same general configuration as it did in 1850 when the estimated population of California was 93,000 persons. The state population grew steadily for the next 100 years, but following World War II, it virtually exploded: between 1950 and 1970 it nearly doubled, growing from 10.6 to 20 million. The 1990 population of 29.8 million represents a 16-fold increase since 1900 and a near tripling since 1950. Of all the coastal states, only Florida has experienced a slightly more dramatic percent increase in population (18-fold since 1900), although the absolute numbers of people is only a third of the California population.

An estimated eighty percent of the state's population lives within 30 miles of the shoreline (Griggs and Savoy 1985). Estimates compiled through our research indicate that approximately 3.6 million people live within three miles of the coast. Land use pressure on the California coastline resulting from population growth over the past 50 years is arguably twice as great as for any other state. With a coastline of 1,100 miles and a population of nearly 30 million persons, there are over 27,000 residents for each mile of coastline.

This population is not equally distributed along the entire length of the coast. Rural Mendocino County, for example, with 120 miles of coastline, has a population of approximately 77,000 or about 640 residents per mile of shoreline. By contrast, Los Angeles County has a 74-mile coastline and a population of 8.65 million people. Each mile of this county's coastline thus "serves" over 117,000 persons, not including the large tourist population drawn to the area.

Because areas with exceptionally high population are likely to have heavier use of coastal resources and higher concentrations of coastal development, it is clear that the type, magnitude, and distribution of coastal hazard risk will vary not only as a result of different physical conditions and geomorphic processes along the coastline, but also as a result of demographic variation. A comprehensive coastal hazards policy must necessarily recognize both geologic and demographic variables within the coastal zone.

California's Coastal Hazards: Types and Distribution

The physical environment of the west coast of the United States is strikingly different from that of either the east or Gulf coasts. Even a casual visitor to the California shoreline will notice the obvious differences between the coastal mountains and seacliffs characteristic of California's western margin and the broad, flat coastal plains, sand dunes, and barrier islands of New Jersey or North Carolina. The east and west coasts of North America have very different geologic histories and, as a result, have very different landforms and pose substantially different problems for human use.

Tectonic plate interactions along the length of the state have produced such diverse features as the San Andreas Fault and its associated earthquakes, the rugged coastal mountains of Big Sur and Mendocino, and the uplifted marine terraces and coastal cliffs which characterize much of the coastline. The entire state, particularly the shoreline, is geologically active; landforms are constantly changing and evolving, although at different scales and rates. Some of these processes operate continuously (waves breaking on the shoreline, for example), others occur seasonally (flooding due to prolonged or high intensity rainfall), while still others occur relatively infrequently (large earthquakes).

A diversity of forces and processes interact on the coast, making it one of the world's most dynamic environments. Waves, tides, winds, storms, rain and runoff, as well as human activity, act to build up, wear down, and continually reshape this continental edge. These forces in turn interact with a wide spectrum of geologic conditions to produce several types of hazard conditions. In California, coastal geologic hazards occur most frequently in the form of shoreline erosion (both seacliff and beach) and coastal flooding (both wave impact and inundation). Human-induced interference with coastal processes (littoral drift, onshore and offshore sand movement, dune and back-beach formation, etc.) can exacerbate hazard conditions.

A 1971 inventory of the California shoreline classified only 14.2 percent as "non-eroding." Of the remaining 85.8 percent, 80.4 miles (4.4 percent) were classified as "critical erosion," with the remainder designated as "non-critical erosion" (COE 1971). The following year, a California Department of Navigation and Ocean Development plan reported that only 120 miles of the ocean shoreline were naturally protected from the open ocean, with an additional 50 miles semiprotected. The remaining 850 miles were classified as "exposed," nearly 250 miles of which were in urban or semi-urban uses in 1972 (COAP 1972).

No inventory of coastal hazards was set forth in the 1975 California Coastal Plan or in the various background reports prepared in support of its development. A subsequent investigation by the California Department of Navigation and Ocean Development (Habel and Armstrong 1977) defined the erosion problem somewhat differently than the COE. Approximately 100 miles (10.9 percent) of the coastline were delineated as eroding with existing development threatened, and an additional 300 miles (29.5 percent) were classified as eroding at a rate fast enough that future development would eventually be threatened. Thus a total of 400 miles (39.4 percent) of the California shoreline were considered to be threatened due to high erosion rates. The most recent inventory of hazardous coastal environments expands the scale of problem areas. In 1985, 16 coastal geologists participated in the preparation of a statewide inventory of coastline conditions, classifying 315 miles (28.6 percent) as "high risk" and an additional 405 miles (36.8 percent) as "caution" (Griggs and Savoy 1985). These data indicate that two-thirds of the California coastline constitutes a significant coastal hazard.

The Extent of Coastal Protection Structures

The 1971 Corps of Engineers inventory of coastal conditions indicated that 26.5 miles of coastline (approximately 2.5 percent) contained some form of "hard" protective structure (COE 1971). In the 14 years between 1971 and 1985, an additional 58.5 miles were armored (Griggs and Savoy 1985). Our recent investigation (conducted through interviews with local government planning staff) indicated that as of 1989, 130 miles (12 percent) of the state's ocean shoreline contains some form of "hard," engineered protective structure, an increase of slightly greater than 50 percent in only four years, and nearly a four-fold increase in 18 years.

When particular areas of the coastline are examined, the increasing degree of protection required to maintain oceanfront property is staggering. For example, 74 percent of the nine miles of northern Monterey Bay now contains "hard" protective structures, as does 77 percent of the 18-mile coastal reach extending from Carpenteria to Ventura. Some 86 percent of the 8 miles of coastline between Oceanside and Carlsbad has been armored, and the 8-mile reach between Dana Point and San Clemente is virtually a continuous system of protective structures (Griggs and Savoy 1985; Griggs 1987).

Adverse Effects of Development on Coastal Process

In recent years there has been a growing realization that many human activities (including damming of coastal rivers and construction of jetties, breakwaters, and coastal protection structures) are adversely affecting beach sand supply and therefore beach stability and longevity. Since the 1950s many southern California coastal rivers have been dammed for water supply and flood control. The dams impound water but also trap sand destined for the coastal beaches and control the high-velocity, large discharge flood flows that transport the greatest volumes of sand to the beaches. Thus the benefits of flood control and increased water supply have been partially offset by the gradual reduction of sand input to the littoral system and the corresponding reduction in the level of coastal protection provided by beaches.

Where seacliff or bluff erosion is a major source of beach sand, which is the case along the shoreline of northern San Diego County, armoring the coastline reduces beach sand supply. Placing coastal protection devices adjacent to sea cliffs which produce significant volumes of beach materials reduces beach sand supply, although no comprehensive evaluation of this impact on beach sand supply has been conducted for the state's coastline.

Along the urbanized seacliffs of southern California, geologic instability has been increased through the addition of large volumes of irrigation water required to maintain lawns and non-native vegetation in the yards of cliff top homes. Landscape irrigation alone is estimated to add the equivalent of 50 to 60 inches of additional rainfall each year to garden and lawn areas. This irrigation has led to a slow, steady rise in the water table that has progressively weakened cliff material and lubricated joint and fracture surfaces in the rock along which slides and block falls are initiated. In addition to these effects, surface runoff discharged through culverts at the top or along the face of the bluffs leads to gullying or failure of weakened surficial materials.

Where a seawall or revetment extends a significant distance seaward of the cliff or bluff, the beach landward of the structure is permanently lost. On a shoreline undergoing net erosion, the beach will eventually disappear as the shoreline migrates landward, and the structure will begin to act as a groin, trapping littoral drift upcoast, and producing erosion downcoast. Thus in the case of a retreating shoreline, the direct effects of seawalls or revetments will be reduced beach width and loss of natural protection from wave attack; structures, utilities, or facilities are protected but the beach is lost.

Since most "hard" protective structures are located on or directly adjacent to public trust lands, the visual effects of such structures on the scenic quality of such public lands is clearly a matter of public policy. The 130 miles of these hard protective structures along the California coast constitute an adverse visual impact which degrades the scenic value of the affected shoreline, and significantly diminishes the natural beauty of these public trust lands. The emplacement of protective structures can also serve as a barrier or impediment to both horizontal and vertical public access.

A Summary Assessment of Coastal Hazard Policies

In spite of a growing body of scientific information on the location and nature of coastal hazards and their associated risks, oceanfront development continues in hazardous areas. Although nearly 20 years have elapsed since the California public voted for the creation of the state's Coastal Commission and 14 years have passed since the legislature passed the California Coastal Act, there remains a wide disparity in governmental responses to coastal hazards. At the time the Coastal Initiative was approved by the voters, the principal issues were environmental concerns, beach access, and wetlands protection. Issues of coastal storm damage, shoreline retreat, littoral drift and sand availability were not as apparent and pressing as they are today. As a result, Coastal Act policy statements and subsequent Interpretive Guidelines are notably deficient in these areas.

For these reasons, as well as the astronomical value of coastal property and a notable lack of political will to confront geologic hazard issues, the translation of the acquired knowledge of coastal hazards and risks into policies and practices appears to be deficient at all levels of government. The objective of this research was to address this deficiency through a systematic analysis and assessment of the coastline policies, plans, guidelines, and practices of local governments and state agencies.

Planning department staff from 34 of the state's 42 coastal cities and 14 of the state's 15 coastal counties were interviewed. Only those jurisdictions whose shorelines were completely urbanized and virtually "built-out" were not included. Although this research project was directed primarily at local government agencies and their policies and practices, because of the extensive involvement of several state agencies in the coastal hazards issue, we also reviewed the policies and practices of three agencies: the Department of Boating and Waterways, the Department of Parks and Recreation, and the Coastal Zone Conservation Commission. State-level staff involved in the coastal programs of these agencies were also interviewed.

Local Government Policies and Practices

Policies and practices regulating oceanfront property and its development vary widely throughout the state. Some communities have articulated policies which encourage community or state purchase of remaining undeveloped oceanfront property, as well as rigorous guidelines and requirements for any new development or protection plans. Others openly encourage shoreline development adjacent to areas of documented high coastal erosion rates. Local politics and economics and a fear of litigation over property rights appear to be the most important factors controlling these policies and practices, rather than the history of shoreline erosion and storm inundation.

Our research focussed on seven specific areas where existing policies and practices raised important questions: (1) Coastal Hazard Identification, Evaluation, and Review; (2) Preparation of Site-specific Geotechnical Studies; (3) Legal Issues Surrounding Hazard Protection Liability; (4) Blufftop Development Policies and Practices; (5) Beach-level Development Policies and Practices; (6) Emergency Condition and Reconstruction Policies; and (7) Policies Governing Coastal Protection Structures. Principal findings for each area are summarized below.

(1) Coastal Hazard Identification, Evaluation, and Review

A basic assumption in the formulation of land use regulations in hazardous coastal areas is that local jurisdictions are able to identify these hazards and adequately assess risks to proposed development. Although several generalized statewide inventories of coastal hazards have been published (COE 1971; COAP 1972; Habel and Armstrong 1977; Griggs and Savoy 1985), additional information is needed on a local or site-specific level. Only five of the local governments interviewed through our research had completed detailed geologic studies focussed on local coastal hazards. Planning department staff cited four primary information gaps: coastal erosion rates, sea level rise and its effects, wave runup, and littoral drift rates. The lack of standards for the design of coastal protection structures was also a frequently cited information gap. There is no agency or organization formally charged with the responsibility for developing this important information. The Coastal Commission employs only two staff geologists. Although these staff are occasionally able to undertake research, nearly all of their time is spent on permit and site review for proposed projects, rather than on developing scientific information in support of advance planning.

One of the most effective methods of land use control in coastal hazard areas is the designation of special zones that permit or exclude specific uses or activities. Twenty-four coastal jurisdictions recognize coastal geologic hazards in some official manner. There is no state directive, however, which ensures recognition of these hazards and the formation of regulatory zones.

Another effective regulatory tool is the use of a geologic hazard ordinance. Although only four local governments use this method, 38 other jurisdictions have comparable regulations which cover some aspect of hazard management. Formal local government designation of coastal geologic hazard areas and land use regulations governing such areas varies widely. The absence of state-level policy requiring local governments to undertake comprehensive identification, evaluation, and land use regulation in hazardous areas is a major reason for this lack of consistency.

(2) Site-specific Geotechnical Studies

Detailed site-specific geotechnical studies are a virtual necessity in order to evaluate coastal hazards. Our findings indicate significant variation in the type and technical adequacy of geotechnical reports and the expertise of personnel preparing such reports. The lack of adopted guidelines governing the preparation of reports, a shortage of qualified local government staff to review reports, the absence of any independent technical review of public agency reports, and a lack of baseline information against which to evaluate the conclusions of reports are the primary reasons for this recurring problem.

(3) Legal Issues Surrounding Coastal Hazard Liability

The costs and risks involved in living directly on the shoreline can be very high for everyone: property owners, local governments, insurance companies and lending institutions, as well as state and federal disaster relief agencies. The risks and potential costs of owning property in a hazardous coastal environment should be fully disclosed to any potential buyer. The 1975 Coastal Plan recognized this need in recommending the following policy, although the subsequent Coastal Act did not include such a provision.

> Geologic hazards information developed by qualified personnel and approved by an appropriate governmental agency for specific areas or sites shall be permanently filed in the public records of the coastal counties. The full reports shall be cited and a summary of all relevant conclusions, understandable to the layman, shall be included as part of the chain of title to property (and be a normal part of a title report) and also as part of the state Real Estate Commissioner's report for subdivisions. (Coastal Commission 1975)

In order to bring existing oceanfront development within safety-based guidelines, it is critical to ensure that all parties involved in the transfer of title to property exposed to coastal hazards be aware of the inherent risks. Only four local jurisdictions presently require such a disclosure.

The threat of lawsuits from coastal property owners has often compromised the regulatory process. This can occur either when building permits are not granted for proposed new construction exposed to geologic hazards or when conditions are imposed on reconstruction permits following coastal storm damage. Local governments and private sector geologic consultants are also concerned over the issue of legal liability in the conduct of their work. The threat of lawsuits over alleged excessive restrictions on private property rights on the one hand, and the consistent and diligent implementation of regulations governing coastal hazard conditions on the other, place these professionals and local government officials in a very difficult situation, particularly given the very high costs of malpractice insurance, the high costs of litigation, and the serious financial constraints on local governments. In response to the threat of litigation, 18 jurisdictions utilize some form of liability release for projects proposed in hazardous areas.

(4) Blufftop Development Policies

Coastal communities from San Diego to Eureka have lost entire ocean-front streets and lots through the ongoing process of bluff retreat over the past century. Moss Beach, Capitola, Isla Vista, Palos Verdes, Encinitas, and Solano Beach are examples of areas where bluff retreat currently represents a significant problem. New developments are still being proposed on eroding or unstable blufftops and older weekend cottages are being torn down and replaced by larger homes.

Because shoreline erosion was not a priority issue at the time the Coastal Act was implemented, state directives on this particular hazard are somewhat vague. Although the Coastal Commission issued Statewide Interpretive Guidelines for determining the geologic stability of blufftop development, there is no state policy establishing safe setbacks from the edge of a seacliff or bluff for any type of development. Some local jurisdictions use a predetermined, fixed setback although these vary from 10 to 320 feet. Others employ a cliff retreat rate (supposedly site specific) and applicable over a specific time period, most commonly a 50-year period.

The Coastal Act is even more lenient in regulating "infill" development; thus it is not surprising to find wide variation in local government interpretations of what constitutes "infill." Many jurisdictions compromise safe setback considerations in "infill" areas (however defined) due to intense pressure from coastal property owners and the real estate community, by assuming that the setback of adjacent existing development is adequate for future construction as well. As bluff retreat continues, this "stringline" approach to determining setbacks is no longer appropriate; it simply extends the hazard exposure to ever more structures.

(5) Beach-level Development Policies

Damage to beach level residential and commercial development was widespread along the California coast in 1978, 1983, and again in 1988. The low-lying communities of Stinson Beach, Rio del Mar, Malibu, Oceanside, and Imperial Beach have been repeatedly damaged by both wave impact and inundation. Despite California's intense beach level development, neither the Coastal Act nor the Interpretive Guidelines specifically recognized the hazards of direct wave impact or wave/tidal inundation (coastal flooding) on beach level structures. Most of the state's coastal jurisdictions have adopted FEMA Flood Insurance Rate Maps which delineate zones that are subject to different degrees of coastal flooding. Although these maps were originally developed for insurance purposes, they now have regulatory status. The lack of state guidelines for safe development at beach-level has led to continued development and reconstruction in hazardous locations.

(6) Emergency Condition and Reconstruction Policies

The Coastal Act contains provisions permitting immediate actions to be taken without obtaining a regular Coastal Development Permit when public or private properties are threatened in emergency situations. However, the experience of coastal jurisdictions with the Emergency Permit process indicates that a serious policy gap exists: there is no link between emergency response procedures established to protect and maintain threatened development and the long-term repair and reconstruction on such sites. Nearly all materials emplaced under emergency conditions provide only short-term protection. Provisions governing the removal of emergency protection structures and the review of the stability or safety of a threatened or damaged principal structure are often ambiguous and have led to considerable litigation.

Coastal Act policies also facilitate the rebuilding of damaged and destroyed structures in essentially the same form and location as the original structure by eliminating the need for a Coastal Development Permit. As a result, rebuilding does not undergo the same scrutiny as new projects, and reconstruction in proven high risk situations is commonplace.

(7) Policies Governing Coastal Protection Structures

Few issues along the California coast are more complex, more poorly understood, or more divisive than the continued use of coastal protection structures. At present there is no comprehensive state policy defining the private or public role of protective devices in geologically hazardous areas. Local government policies and practices vary widely. Many communities will not allow development of a parcel if a coastal protection structure is required to insure survival of the dwelling during its design life. At the opposite end of the spectrum, some communities require that the construction of a protective structure be part of the normal development process.

Because of high construction costs ($750 to $3000/linear foot or $4 million to $16 million/mile) and high maintenance and repair costs, shoreline protection is a major investment, often subsidized by state or federal programs or insurance monies. The existing level of coastal protection in California represents an investment of between $500 million and $2 billion (1990 dollars) in an attempt to halt erosion along 130 miles of shoreline. Private property owners and public agencies alike must realize that armoring the shoreline is a very expensive, and often only temporary, solution to the problem. It is time to take a critical look at the costs and benefits of additional shoreline protection. At least two states, North Carolina and Maine, have recently enacted legislation which prohibits the construction of "hard" protective structures. Relocation of buildings to safer sites or replenishing the beach's sand supply are the favored alternatives in those particular states.

Although relocation of a structure may be less costly than armoring the shoreline, this approach is rarely a seriously considered option since most shoreline residents are unwilling to forego the loss of an oceanfront view. However, relocation, dismantling, or abandonment of oceanfront homes will soon be the only possible alternative at some sites due to difficult geologic conditions, as well as land ownership and access considerations.

A number of southern California's coastal communities are now evaluating beach nourishment as a solution to shoreline erosion problems. However, there are many issues which need to be resolved prior to embarking on any large scale nourishment project. The availability of large volumes of sand of the appropriate size, the impacts of removing the sand from the source area and transporting it to the beach, and the magnitude and distribution of costs affect the feasibility of such programs. Durability and longevity of nourished beaches is another concern. Due to the high littoral drift rates along most of the California coast, the life span of nourished beaches in most locations is expected to be relatively short. A recent study concluded that 18 percent of

California's nourished beaches lasted less than one year, and 55 percent lasted only one to five years (Pilkey and Clayton 1987).

State Agency Policies and Practices

In 1978, the California Secretary of Resources promulgated a Shoreline Erosion Protection Policy to govern state agency activities in shoreline environments. This declaration provided both a clear description of the role of each department within the agency in dealing with the shoreline and a comprehensive set of policies which are as appropriate today as they were a decade ago. In spite of this policy, there is considerable variation in the actual policies and practices of the individual agencies; in some cases, there is a notable lack of any clear policy direction. The policy hierarchy governing these agencies extends downward from State Code, through commission-level policy, and finally down to department-level policy, guidelines, in-house memorandums, etc. The vague or generalized wording of many such declarations, combined with the separation and autonomy of the local district or regional offices of some agencies and the constant influence of political figures, has led to many state projects that are inconsistent with existing Coastal Act policy. In the words of one state agency staff member, "policy is only for staff, not decision makers."

Two state agencies—the Department of Boating and Waterways and the Department of Parks and Recreation—have substantial authority regarding the expenditure of state funds for shoreline erosion control. Brief summaries of these agencies' practices follow.

Department of Boating and Waterways

The Department of Boating and Waterways responds to requests by local governments for technical and monetary assistance in shoreline protection projects. Over the past 20 years the agency has expended over $26 million on projects involving shoreline protection and beach nourishment, typically with a funding distribution of 75 percent state, 25 percent local. The department cannot fund all of the requests received. It has no overriding policies governing either their beach erosion-control program or their allocation of funds. Although the department carries out limited research and has funded some institutional research in the past, the state has not allocated permanent funds for these efforts. As a result, the agency works in a reactive and largely ad-hoc mode, responding to individual requests as they are submitted yearly, rather than operating under a comprehensive program governed by clear and sound policy and explicit criteria for establishing priorities.

Department of Parks and Recreation

The California Department of Parks and Recreation is responsible for managing over 210 miles of the state's 1,100 miles of coastline. There are 117 individual DPR units along the coast, each with an official designation (State Beach, Park, Reserve, etc.) that influences the management, development, and operation of the particular unit. The storms of 1978, 1980, 1982, and 1983 resulted in extensive damage to State Park facilities, requiring an expenditure of $4.8 million for repairs. Beach-level campgrounds, access roads, parking lots, stairways, restrooms, seawalls, and other support facilities were damaged, rebuilt and, in a number of cases, damaged again.

Due to the costs involved in continual reconstruction in some of these hazardous locations, a new coastal erosion policy was developed by the department following the 1983 storms, with a goal to "avoid construction of new permanent facilities in areas subject to coastal erosion, and to promote the use of expendable or movable facilities where the expected useful life is limited due to their location in erosion prone areas." The avoidance of hazardous areas or the retreat from sites where repeated storm damage through either wave impact or shoreline erosion has taken place, are logical approaches for an agency which is focussed primarily on providing recreational areas for the public.

Despite this official policy, major reconstruction of a seawall and beach level facilities at one site took place again, although there were seven prior episodes of destruction. This effort was clearly contrary to the established policy. There is considerable uncertainty in the minds of some state staff as to the status of this policy and whether or not local staff are even aware of its existence. State staff also express considerable cynicism with respect to the lack of enforcement of state policy by decision-makers at all levels of government, observing that policy invariably takes a back-seat to political pressure.

California Coastal Zone Conservation Commission

The limited number of technical staff, the heavy project review demands, and the advisory nature of guidelines have combined to limit the State Coastal Commission's role in coastal hazard evaluation. As such, local governments have retained the primary responsibilities for setting and implementing standards governing development in hazardous locations, although regional-level Coastal Commission staff frequently provide technical assistance to local jurisdictions.

These concerns raise serious questions regarding the effectiveness of California's governance of coastal hazards. There appears to be considerable variation in policies and practices within and among state agencies. Policy language is often so ambiguous as to permit the approval of virtually any project, and the consistent translation of policy from the state to district or unit levels is also a problem.

State Actions To Improve Coastal Hazard Policies

The California Legislature should take action to improve the appropriateness and effectiveness of coastal hazard policies. Such actions should require local governments and state agencies to make the policy changes described below.

Local Government Level

(1) Coastal Hazard Identification, Evaluation, and Review

Every local government making coastal land use decisions should have a comprehensive and accessible information base that is developed through adequate scientific and technical studies. Each jurisdiction should designate special geological hazard areas where detailed site-specific studies are necessary. A comprehensive coastal geologic hazards ordinance should be required for every coastal jurisdiction with identified geologic hazards.

(2) Site-specific Geotechnical Studies

Consistent geologic and geotechnical report guidelines specifying both the scope and content of reports for all types of coastal hazard investigations should be required as a matter of state policy. A process of peer review of these reports by qualified professionals is needed in order to ensure complete investigations, sound conclusions, and appropriate mitigation measures.

(3) Legal Issues Surrounding Coastal Hazard Liability

Geologic hazard disclosure statements and deed posting of existing geologic and geotechnical reports relevant to specific parcels should be required statewide. Local governments should receive state technical assistance in the formal designation of coastal hazards and legal assistance and support in instituting appropriate restrictions and regulations in areas of recognized high geologic risk, thus reducing litigation that can render the local government planning and regulatory process ineffective.

(4) Blufftop Development Policies

A minimum blufftop setback should be required for all new construction, and all reconstruction or remodeling which increases the value of the structure by more than 25 percent. This setback should be based on site-specific erosion rates and a structural life of 100 years without reliance on a protective device. A minimum setback of 25 feet should be required, and the concept of a "rolling setback" that moves landward over time should be used in delineating this setback.

(5) Beach-level Development

Beach level development and reconstruction or remodeling which increases the value of a structure by more than 25 percent should be permitted only when safety from wave impact and inundation throughout a projected 100-year lifetime of the structure can be demonstrated without reliance on a protective device.

(6) Emergency Condition and Reconstruction Policies

Definitive guidelines should be adopted to govern actions taken under postemergency conditions, including a timetable for the removal of any materials emplaced for emergency protection. Coastal jurisdictions must recognize hazardous conditions and work towards reducing the need for emergency permits by siting all new development and reconstruction away from hazardous locations. Reconstruction which increases the value of a structure by more than 25 percent, or where storm or erosion damage is greater than 25 percent of the value of the structure, should be subject to the same geologic hazard review and evaluation process for safety and long-term stability (including obtaining a Coastal Development Permit) as any proposed new development.

(7) Policies Governing Coastal Protection Structures

Proposed new shoreline development should only be permitted if it is safe from coastal hazards for 100 years without reliance on a protective device. Alternatives to protective devices, for both private and public projects, should be vigorously pursued. Hard protective structures should be permitted only when a complete environmental assessment can make the following findings: (1) historical erosion rates substantiate the need for a solution; (2) the structure will not produce a significant loss of public beach; (3) existing public access will not be reduced; (4) scenic values will not be significantly reduced on contiguous public trust lands; and (5) the proposed structure is the most acceptable and durable long-term solution. Proposals for new protective devices should be carefully reviewed by qualified professionals and the effectiveness of any adjacent protective structures should be considered prior to granting permits for new structures.

State Agencies

Department of Boating and Waterways

The Department of Boating and Waterways should establish clear priorities for shoreline protection projects, including a clarification of which projects are appropriate for state funding, which have high, moderate, or low priority, and which will not be funded. Evaluation criteria should include (1) ownership of property being protected (private or public); (2) effectiveness and projected lifetime of proposed project; (3) options or alternatives available; and (4) both short- and long-term environmental impacts. The state should not attempt to fund all proposals for shoreline protection and beach nourishment. Proposed new "hard" protective structures should receive particularly close scrutiny and should be funded only when compelling circumstances so warrant.

Department of Parks and Recreation

The practices of the Department of Parks and Recreation should reflect the agency's adopted policy, which prohibits construction of new facilities in areas subject to coastal erosion. Policies governing construction, reconstruction, maintenance and protection in hazardous shoreline areas should be applied uniformly at both the state and local-unit levels.

Coastal Zone Conservation Commission

The technical and scientific responsibility for coastal geologic hazard evaluation should be transferred from the Coastal Commission to the California Division of Mines and Geology as detailed below.

A Comprehensive State-Level Coastal Hazards Program

Significant changes are needed in the policies and regulations of the the State of California governing development in coastal hazard areas. An expansion and refinement of policies and practices is necessary in order to achieve a consistent and effective response to the continuing pressure to develop in these areas. The marked inconsistencies among the local governments and state agencies that regulate development reflect a lack of state direction and reveal a heavy influence of local economics and politics.

Through a process of hazard recognition and evaluation and a subsequent standardized set of avoidance, mitigation or hazard reduction policies incorporating the actions set forth above, the private and public losses from future shoreline erosion, storm impact and sea level rise can be significantly reduced. The objective is to reduce the number of people, as well as dwellings, structures, and utilities, both public and private, directly exposed to the hazards of shoreline erosion, wave impact, and inundation. The Alquist-Priolo Act, which established Special Studies Zones along California's active faults, is an appropriate model to follow for the coastline.

Due to the lack of responsibility within any existing state agency for systematically evaluating shoreline hazards and recommending statewide policy, such authority should be vested within the California Division of Mines and Geology, an agency already charged with evaluating California's natural hazards and resources.

The modest funding required to implement such a program along the shoreline would have a high benefit-to-cost ratio. Initial investigations would establish the general hazard or special studies zones which would then be delineated on official state maps. Any development or significant changes in land use proposed within these areas at the local government (private or public) or state level would require complete geologic hazard investigations, report review by an independent qualified professional, and appropriate setbacks and mitigation measures. Geologic report guidelines comparable to those outlined in the Alquist-Priolo program and by the California Division of Mines and Geology should also be adopted.

A reduction in both risk exposure and public and private economic losses from geologic hazards in the coastal zone are objectives which need to be realized. The Coastal Act focussed on what were deemed to be the critical issues of the time but was deficient in treating geologic hazards. Although some local governments have been effective in dealing with coastal hazard issues, it is now time for a state-level program that provides a consistent, efficient, and streamlined approach for land use regulation in hazardous coastal areas.

Acknowledgments

The research for this study was supported by a grant from the California Policy Seminar Program, a joint University of California/State Government Program.

References

Burton, I., Kates, R.W., and White, G.F., 1978. The Environment as Hazard. New York: Oxford University Press.

California Coastal Zone Conservation Commission, 1975. California Coastal Plan. San Francisco, California.

California Department of Navigation and Ocean Development, 1972. California Comprehensive Ocean Area Plan. Sacramento, California.

Fulton-Bennett, K. and Griggs, G.B., 1986. Coastal Protection Structures and their Effectiveness. Joint Publication of the State of California Department of Boating and Waterways and the Institute of Marine Sciences at the University of California at Santa Cruz. 48pp.

Griggs, G.B., 1986. "Reconstruction or Relocation: Viable Approaches for Structures in Areas of High Coastal Erosion." Shore and Beach 54: 8-16.

Griggs, G.B., 1987. "California's Retreating Shoreline: The State of the Problem." Proc. Coastal Zone '87. Seattle, Washington: A.S.C.E. pp 1370-1383.

Griggs, G.B. and Savoy, L., 1985. Living with the California Coast. Durham, North Carolina: Duke University Press. 344pp.

Griggs, G.B., Pepper, J.E., and Jordan, M.E., in preparation. California's Coastal Hazards: A Critical Assessment of Existing Land Use Policies and Practices. Final Report to the California Policy Seminar Program.

Habel, J.S. and Armstrong, G.A., 1977. Assessment and Atlas of Shoreline Erosion Along the California Coast. California Department of Navigation and Ocean Development. Sacramento, California.

Pilkey, O.H. and Clayton, T.D., 1987. "Beach Replenishment: The National Solution?" Proc. Coastal Zone '87. Seattle, Washington: A.S.C.E. pp 1408-1419.

State of California, 1972. The California Coastal Zone Conservation Act of 1972 (Proposition 20).

State of California, 1976. California Coastal Act of 1976 as amended January 1988. Public Resources Code, Division 20.

United States Army Corps of Engineers, 1971. National Shoreline Study: California Regional Inventory. South Pacific Division, San Francisco, California.

WASHINGTON STATE COASTAL HAZARD INITIATIVES

Douglas J. Canning
Shorelands and Coastal Zone Management Program, Washington Department of Ecology

Introduction

The development of coastal hazards policy in Washington State results from the state-local partnership mandated in the Washington Shoreline Management Act. The state law and regulations set out broad goals and the means of complying with those goals. Local governments adopt Shoreline Master Programs that collectively form the state's Shoreline Master Program. The Department of Ecology has oversight authority to assure that local master programs are consistent with state law.

Currently, the Department of Ecology is addressing three coastal hazard policy issues: erosion and landsliding, sea level rise, and incorporation of the public trust doctrine into management and permitting decisions.

Coastal Erosion Management

No comprehensive assessment of coastal erosion has been completed for Washington State. The rate of erosion along Washington's shoreline is known to be highly variable. In some areas erosion is simply not a problem, whereas in other places erosion is relatively rapid. Erosion is rarely catastrophic and life threatening, but it can result in losses of property. (Nowhere in Washington is the rate of erosion as rapid and threatening as it commonly is along portions of the Gulf and Atlantic coasts.)

Erosion in Washington falls into two basic categories: beach erosion and bluff retreat. The former is often the result of a loss of sediment supply, whereas the other may be largely related to the local geology.

The southwestern coast of Washington consists of wide sand spits and large, protected estuaries. The beaches of Grays Harbor and Pacific counties are largely accretional, although localized erosion has occurred at the north Columbia River jetty, at the entrance to Willapa Bay, and at Westport near the south jetty of Grays Harbor. There are growing concerns that the historic accretion of the southwest beaches may not continue due to the trapping of sediment by dams on the Columbia River and the possible acceleration in sea level rise postulated with global warming (Phipps 1990).

The shorelines of Puget Sound consist largely of unconsolidated glacial materials that are vulnerable to erosion. Keuler (1988) mapped erosion patterns along various types of shoreline in northern Puget Sound and measured erosion rates of about 5 to 30 centimeters (0.1 to 1.0 feet) per year. The range of 6 to 9 centimeters (0.2 to 0.3 feet) per year seems most common. The *Coastal Zone Atlas* (Ecology 1978) included a qualitative estimate of erosion along the entire Puget Sound shoreline and found over 30% of the shoreline to be actively eroding. A much larger portion may be subject to more gradual or to episodic erosion.

Rates of shoreline retreat are slow enough in most of Washington that little attention is paid to locating structures away from the shore. No local governments regulate setbacks based on erosion rates (Canning 1991a). The common perception, however, is that the risk is greater than it truly is. The general response to erosion in Puget Sound is the armoring of the shoreline, primarily with concrete bulkheads, although alternatives are recommended (Canning 1991b). Most local government regulations conditionally permit shoreline armoring to protect structures; this provision has often been misinterpreted to include protection of property. As of the mid-1970s, roughly 8% of the Puget Sound shoreline was armored (Downing 1983), largely in urban areas, but this number has certainly increased in the last 15 years. The greatest increases have occurred along residential shorelines.

Coastal landsliding is often considered to be a simple coastal erosion problem. The geologic sequence of sands and gravels intermixed with clays and tills typical of Puget Sound bluffs is a highly unstable combination. The intermediate sand and gravel unit is not stable, particularly when saturated with water. It is also easily eroded by waves or by surface runoff. Groundwater concentrates at the base of the porous units, since it cannot pass downward into the underlying clays or tills. Groundwater seeps from bluff faces carrying material with it and undercutting overlying materials. When the sand and gravel fails, the overlying Vashon Till also collapses.

Over 30% of Puget Sound's shoreline is mapped as unstable; in some counties the percentage is much higher (Downing 1983). These unstable areas include many old landslides, as well as many potential slides. Many of these old landslides have already been built on, out of either ignorance or overconfidence. Where the geology can be mapped, the likelihood of landsliding can often be predicted. Landsliding can also be favored by improper clearing and grading practices and by poor drainage in upland areas.

Landsliding risk is greatest for development along the edge of unstable bluffs or at the base of these bluffs. Development on existing landslide deposits is clearly hazardous.

Concern has grown in the state about the cumulative impacts of bulkheading on both the physical and biologic function of the shoreline. Shorelands has an ongoing program in this area to address the effects of shoreline hardening (Terich and Schwartz 1990), alternatives to shoreline hardening (Terich, Schwartz, and Johannessen,1991a, 1991b), and the rate and character of shoreline hardening.

During August 1991 the Department of Ecology received requests from the Thurston County and Mason County commissioners that the department undertake the preparation of a programmatic environmental impact statement (EIS) on the cumulative effects of bulkheading and other forms of shoreline hardening.

We believe that a programmatic EIS could be a useful and educational process for assembling and disseminating information on the problems associated with large-scale shoreline hardening, as well as for addressing viable alternatives. A programmatic EIS could also provide a firm foundation for local government decisions or regulatory reform. We are seriously considering carrying out the programmatic EIS as requested, our budget permitting.

The policy issue we face is the balancing of the protection of private rights in real property with the protection of public rights in natural resource properties. Owners of upland properties feel a strong need to protect their investments in land and buildings. Shoreline armoring is common even of properties little affected by erosion. Extensive shoreline armoring, however, is destructive of the public resource properties in the intertidal and shallow subtidal habitats. Juvenile pink and chum salmon require shoreline shallows to escape predation on their migration out to sea. Pacific herring and surf smelt require intertidal and subtidal habitats for spawning. Shoreline armoring impinges upon these habitats and over the long term degrades them.

Sea Level Rise

Washington's sea level rise initiative began in 1988 when we first asked ourselves, "Is this a real issue for Washington State?" Clearly the answer was yes, and for two reasons. First, the existing rate of sea level rise, in conjunction with subsidence within Puget Sound, is sufficient to explain the slight but chronic erosion of unconsolidated Puget Sound shorelines. Second, accelerated sea level rise due to global climate change could have substantial effects on specific coastal locales.

A Sea Level Rise Task Force was convened, consisting primarily of state resource agencies. The recommendations of the task force fell in three basic areas: the need for information on the effects of vertical land movement on relative sea level rise; the need for more certain sea level rise scenarios; and potential future policy issues. Potential policy issues were identified as

- siting standards and protection alternatives for private and public coastal facilities and developments.

- cleanup and closure standards for coastal solid and hazardous waste disposal sites, which would need to be inventoried, characterized, and mapped.
- impacts on marine resources such as wetlands and shallow-water habitats.
- seawater intrusion of coastal aquifers, especially where seawater intrusion is an existing problem.

Following the recommendations of the Sea Level Rise Task Force, in 1989 Shorelands initiated a series of technical and policy studies and assessments. A study of vertical land movements indicated that uplift along portions of Washington's Pacific Ocean coast (up to 24 centimeters a century) would mitigate near term accelerated sea level rise, but that subsidence within Puget Sound (up to 24 centimeters a century) would aggravate sea level rise (Shipman 1989). An assessment of the state-of-the-knowledge, likely impacts, and potential policy issues was prepared (Canning 1990). Research into wetlands sedimentation and subsidence was carried out at three locations in northern Puget Sound by Western Washington University (Beale 1990). Results confirmed that sea level rise in Puget Sound has been consistent with global averages ranging from 10 to 15 centimeters a century.

In the near term, the threat is moderate and is caused by the existing rate of sea level rise (about 12 centimeters a century) as mitigated or aggravated by regional vertical land movements. Along the Pacific Ocean coast, uplift exceeds the existing rate of sea level rise in the vicinity of Neah Bay and the Columbia River estuary, producing a net relative sea level fall. Within Puget Sound vertical land movement ranges from zero in the San Juan Islands-Skagit Bay-Sequim area, to about 24 centimeters a century at Tacoma. The maximum relative sea level rise is about 36 centimeters a century (1.2 feet a century) at Tacoma.

Currently the generally accepted scenarios for accelerated sea level rise due to global climate change range between 0.5 meters and 1.5 to 2.0 meters by the year 2100. If we take into account vertical land movement, a 1.0 meter acceleration would result in a 0.5 meter sea level rise in Tacoma by 2050, in Seattle by 2055, and in Friday Harbor by 2067. Under this scenario, the uplift at Neah Bay would delay occurrence of a 0.5 meter rise until about 2080.

At present, existing sea level rise is causing or aggravating shoreline erosion and bluff landsliding. As noted above in the Coastal Erosion Management section, erosion and erosion management are currently issues of concern with coastal managers in state resource agencies and local planning departments. Over a period of decades, accelerated sea level rise is expected to aggravate existing erosion and landsliding problems. Seawater intrusion of coastal aquifers, which is a problem on the islands of north and central Puget Sound and along Hood Canal due to groundwater withdrawals, will be aggravated. Areas currently at risk of flooding will experience more frequent and more severe flooding; areas just above the flood zone now will become subject to flooding. Wetlands and possibly other low-lying coastal areas will be subject to inundation.

The types of areas at risk are primarily unconsolidated shorelines, low-lying areas, coastal wetlands, accreted shoreforms, intertidal and shallow water habitats, and major river deltas. No quantitative studies have been carried out to delineate the extent or degree of risk.

Unconsolidated shorelines include most Puget Sound, Grays Harbor, Willapa Bay, and Columbia estuary shorelines. The rocky shores of the San Juan Islands are a notable exception. Unconsolidated shorelines are susceptible to erosion. The present long-term average erosion rates of a few tenths of a foot per year are expected to increase with any acceleration in the rise of sea level.

Low-lying areas will be threatened from storm surge, flooding, or inundation, depending on their elevation, the rate of acceleration, and the technical and fiscal feasibility of protection. Urban areas potentially threatened by storm surge, flooding, or inundation are typified by the central business district of Olympia, the state's capitol. Thurston Regional Planning Council and the City of Olympia are nowcarrying out an assessment of the Olympia CBD under a Coastal Zone Management grant; the assessment report will be completed by June 1992. In other developed low-lying areas, investments in agricultural lands, public highways or air ports, residential real estate, or other facilities are at risk.

Coastal wetlands will be threatened by erosion or inundation. An assessment of selected Puget Sound shorelines is being carried out by Holcomb Research Institute in cooperation with the Washington Department of Ecology under a U.S. Environmental Protection Agency grant; the final project report is scheduled for publication by the U.S. EPA in spring 1992.

Accreted shore forms (coastal barriers, sand spits, and so on) will be threatened by erosion, storm surge, flooding, or inundation. The principal accreted shore forms have been inventoried and characterized (Shipman 1991).

Intertidal and shallow-water habitats will be at risk from a likely secondary effect of response to sea level rise. As some shorelines become hardened (bulkheads, sea walls, riprap, etc.) to resist erosion, the shoreline will become fixed in place, and rising sea level will steadily lessen the extent of intertidal and shallow-water habitats, possibly eliminating intertidal habitat in some locations. Intertidal and shallow-water habitats are important for the rearing and migration of juvenile salmon, spawning of Pacific herring and surf smelt, and the life cycle of certain shellfish.

Major river deltas will be subject to the same threats as low-lying areas and accreted shore forms. Additionally, the delta waters will be subject to salinity changes affecting the general ecology. The major river deltas of greatest concern are the Skagit, Snohomish, Puyallup, and Nisqually on Puget Sound; the Chehalis on Grays Harbor; and the Willapa on Willapa Bay. Other deltas which might be of concern are the Union, Skokomish, Hamma Hamma, Duckabush, Dosewallips, and Quilcene on Hood Canal. River deltas and adjacent valley bottoms will be susceptible to seawater intrusion and a forcing of the water table to higher elevations. This in turn will lead to soil saturation and tertiary effects of decreased soil drainage and increased duration of flooding, increased corrosion of underground tanks and pipes, the need to drain agricultural lands, and decreased effectiveness of sewage drain fields or possibly the need to install sewerage systems.

A Policy Alternatives Study to review and evaluate existing legal authorities and potential policy response alternatives was carried out by Battelle's Human Affairs Research Centers under contract to Shorelands (Klarin et al. 1990). The analytical portion of the study addresses regulatory approaches, economic and market strategies, and governmental programs for a variety of issues:

- Wetlands protection and preservation
- Protection and preservation of shallow-water and estuarine habitats
- Seawater intrusion
- Groundwater contamination
- Beach, shoreline, and bluff erosion
- Preserving public access and recreation opportunities
- Planning, permitting, and remediation of facilities and infrastructure
- Shoreline floodplain hazards management

An assessment of the approaches of local governments to sea level rise response will be evaluated through the Coastal Zone Management Act Section 306 and 306A planning and construction grants program. Beginning in Washington's Fiscal Year 1992 (July 1991 to June 1992), Section 306 and 306A grant projects must be engineered and constructed for the existing rate of sea level rise (including subsidence) and must include conceptual planning for accelerated sea level rise preparedness (Shorelands and Coastal Zone Management Program 1991). This type of approach to sea level rise preparedness is similar to that of the San Francisco Bay Conservation and Development Commission (Bay Plan Amendment No. 3-88 Concerning Sea Level Rise, Adopted January 5, 1989) and the U.S. Army Corps of Engineers (Circular No. 1105-2-186, Guidance on the Incorporation of Sea Level Rise Possibilities in Feasibility Studies, Issued April 21, 1989).

Public Trust Doctrine

The private rights and public use of tidelands and shorelands relating to the Public Trust Doctrine is another issue of growing concern in Washington. In simple terms, the Public Trust

Doctrine is a judicial statement of the state's responsibility to manage public property in the public interest. The public property interests include rights of navigation, fishing and shellfishing (both commercial and recreational), and by many interpretations, the environmental quality necessary to support fish and shellfish habitat in navigable and estuarine waters.

The ownership of all tidelands was transferred to the state at the time of statehood under the equal footing doctrine of the U.S. Constitution, wherein each new state entering the union obtained status equal to the original thirteen states. Importantly, the original states followed English common law, whereby the state governments held the tidelands in trust for all the people—the Public Trust Doctrine.

Through the years, over 60% of Washington's inland marine water tidelands were sold to private upland owners (Conte 1982). Public use of shorelines in Washington has traditionally respected private ownership of tidelands. Many private tideland owners have excluded the public by installing "no trespassing" signs and occasionally by physical threats. However, these actions may be in violation of the Public Trust Doctrine. There is currently an emerging school of thought, supported by recent court cases, that says that sales of tidelands never included all rights of property ownership and were subject to the Public Trust Doctrine. The courts have held that a government cannot relinquish its public trust responsibilities. The act of selling tidelands does not negate the projections provided by the Public Trust Doctrine. Therefore, in the case of tidelands as related to the doctrine, the issue is, just what public rights do exist?

In a 1969 case, *Wilbour v. Gallagher*, the Washington State Supreme Court declared that the public has the right to go where the navigable waters go, and ordered a fill in Lake Chelan removed. *Wilbour v. Gallagher* is considered to be the legal basis for the state's Shoreline Management Act (SMA). At the time, the Supreme Court did not explicitly mention the Public Trust Doctrine.

In state courts the doctrine was largely unrecognized by name until the late 1980s. It was not until the case of *Caminiti v. Boyle* that the Public Trust Doctrine was recognized by name in a Washington State Supreme Court case. That recognition was further reinforced by the *Orion Corp. v. State* case. Furthermore, the court declared that the Public Trust Doctrine had always existed under Washington law even though not explicitly cited.

The implications for the public and for shoreline property owners can be interpreted in several ways. One way would be that the permitting process established by the SMA is the means of protecting the public's interest in the shoreline and the tidelands, while allowing for necessary development on shoreline property. Part of the reasoning for this is the public review, comment, and appeals procedures that are built into the permit process. Alternatively, the single family residence exemption from the permit process provided by the SMA may be an inadequate protection of the public trust interest and could possibly be subject to court challenge. Third, allowing a bulkhead or other structure to be built which interferes with the natural shoreline erosion and accretion process may also be an inadequate protection of the Public Trust Doctrine's mandate to protect the public interest in shorelands and shoreland resources.

Shorelands has sponsored an evaluation of the implications of the Public Trust Doctrine for coastal zone management in Washington State. This study is based upon a recently completed nationwide study (Connors, Laurence, Columbia, Archer, and Bowen 1990). The Washington analysis (Johnson, Goepple, Jansen, and Paschal 1991) has just been completed.

Conclusions

Coastal hazard initiatives in Washington State center around erosion issues—long term and short term, real and perceived, physical and legal. As noted above, the central policy issue relates to a balancing of public and private property rights. Central to that balancing is a heightened awareness of the state's responsibilities under the Public Trust Doctrine.

References

Beale, H. 1990. Relative rise in sea level during the past 5,000 years at six salt marshes in northern Puget Sound, Washington. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Canning, D.J. 1991a. Shoreline bluff and slope stability: management options. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Canning, D.J. 1991b. Marine shoreline erosion: Structural property protection methods. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Canning, D.J. 1990. Sea level rise in Washington state: state-of-the-knowledge, impacts, and potential policy issues. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Connors, D.L., K. Laurence, S.C. Columbia, J.H. Archer, and R. Bowen. 1990. The National Public Trust study. Coastal States Organization.

Conte, K.R. 1982. The disposition of tidelands and shorelands: Washington state policy, 1889-1982. Unpublished master's thesis. The Evergreen State College, Olympia, Washington.

Downing, J. 1983. The coast of Puget Sound: its processes and development. Washington Sea Grant, University of Washington Press, Seattle.

Ecology, Washington State Department of. 1978. Coastal Zone Atlas of Washington (several volumes).

Johnson, R.W., C. Goepple, D. Jansen, and R. Paschal. 1991. The public trust doctrine and coastal zone management in Washington state. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Keuler, R.F. 1988. Map showing coastal erosion, sediment supply, and longshore transport in the Port Townsend 30- by 60-minute quadrangle, Puget Sound Region, Washington. Map 1198-E, Miscellaneous Investigations Series, U.S. Geological Survey.

Klarin, P., K.M. Branch, M.J. Hershman, and T.F. Grant. 1990. Sea level rise policy alternatives study: Volume 1, Alternative policy responses for accelerated sea level rise and their implications; Volume 2, An analytical review of state and federal coastal management systems and policy responses to sea level rise. Battelle Human Affairs Research Centers for Shorelands and Coastal Zone Management Program, Department of Ecology, Olympia.

Phipps, J.B. 1990. Coastal accretion and erosion in southwest Washington: 1977-1987. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Shipman, H. 1991. Coastal barriers and accreted landforms in Washington state: Inventory and characterization. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Shipman, H. 1989. Vertical land movements in coastal Washington: implications for relative sea level changes. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Shorelands and Coastal Zone Management Program. 1991. Sea level rise planning, engineering, and construction policies for Shorelands-funded projects. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Terich, T.A., and M.L. Schwartz. 1990. The effect of seawalls and other hard erosion structures upon beaches: an annotated bibliography. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Terich, T.A., M.L. Schwartz, and J. Johannessen. 1991a. Annotated bibliography of beach nourishment literature, with applicability to Puget Sound and summary, guidelines, and methodology. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Terich, T.A., M.L. Schwartz, and J. Johannessen. 1991b. Annotated bibliography of vegetative erosion control literature. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Ocean Shore Protection Policy and Practices in Oregon

James W. Good
Coastal Resources Specialist, Extension Sea Grant Program
College of Oceanic and Atmospheric Science, Oregon State University

Introduction

The Oregon coast is renowned for its rocky shores, rugged beauty, and accessible, uncrowded beaches. Long, gently sloping beaches backed by cliffs front much of the coast, interrupted only by rocky basalt headlands that extend into the sea. Steep-faced pocket beaches nestle within short stretches of rocky coastline. Barrier sand spits with dune complexes enclose the estuaries of more than a dozen coastal rivers. Other beaches form the trailing edge of landward-migrating dune sheets.

These ocean beaches are also public recreation areas by virtue of customary public use, far-sighted legislation early in the century, and a subsequent series of laws that culminated in the historic 1967 Beach Bill. Though the path that led to the preservation of public beach rights was marked with controversy—numerous legislative battles, landmark court cases, public initiative petitions, and media blitzes—today we enjoy free use of both the wet and dry sand portions of Oregon beaches. With an unparalleled system of state parks, waysides, and other access points along the shore, these beaches are among the most accessible in the country.

The Oregon coast is also one of the most dynamic in the world (see Komar, this volume). Severe winter storms, large waves, strong tides and nearshore currents, and rain and high winds cut into beaches and dunes. They undermine and batter sea cliffs, causing slumping and slides, and flood low-lying coastal lands. In recent years, the vulnerability of the coast to large, locally generated earthquakes and tsunamis has become widely accepted in the scientific community, adding the threat of catastrophic hazards to the reality of the chronic ones we experience (see Madin, this volume).

As pressure increases for coastal development, the more hazardous sites avoided earlier fill in with houses, motels, and condominiums. Also, earlier development along much of the coast becomes threatened as the shoreline gradually recedes. Episodic erosional events and other chronic hazards increasingly take their toll on this development. The response to these hazards has generally been to construct riprap revetments, seawalls, and bulkheads that are designed to fend off waves, stabilize cliffs, and retain the shoreland (see Kraus and McDougal, this volume). As more development occurs adjacent to the beach, normal episodes of erosion create a demand for more and more structures. These development and shore protection practices, in turn, have raised questions about the effectiveness of Oregon's coastal management policies—policies that were designed to protect the scenic values, recreational qualities, and accessibility of Oregon beaches; control development in hazardous areas; and promote nonstructural alternatives to revetments, seawalls, and other shoreline armoring. These concerns have been magnified by research which suggests that engineering solutions to coastal hazards sometimes lead to more problems, including accelerated erosion of the beach and adjacent properties, loss of cliff-supplied sand to the beach system, and gradual beach narrowing in the face of sea level rise.

In this paper, I examine the effectiveness of Oregon's coastal management policies designed to mitigate the impacts of natural hazards on public beach resources and private oceanfront development. I first outline relevant laws, policies, and decision-making processes. I then examine and evaluate the implementation of these policies, based on a Sea Grant-sponsored case study of shore protection and land use decisions along the 16-mile long Siletz littoral cell on the central coast (Good 1992). Finally, I describe the strategy being used by state coastal managers to improve the policy basis for mitigating natural hazards on the Oregon coast.

Coastal Natural Hazards Management in Oregon

Local, state, and federal agencies each have programs and policies related to the management of natural hazards along the Oregon coast. These programs and policies are summarized by function and governmental level in table 1. Three of the functions—information and mapping, development planning and siting, and shore protection—are discussed in more detail below. The state and local authorities listed are part of Oregon's coastal management program.

Hazards Research, Information, and Mapping

The principal state agency for hazards research, mapping, and technical assistance is the Oregon Department of Geology and Mineral Industries (DOGAMI). Much of the funding for DOGAMI research and hazard assessment comes from the U.S. Geological Survey (USGS), the Federal Emergency Management Agency (FEMA), and other federal agencies. Also contributing to our understanding of coastal processes and their influence on shorelines has been Sea Grant and other federally sponsored research carried out at Oregon State University, the University of Oregon, and Portland State University.

The state coastal management agency, the Department of Land Conservation and Development (DLCD), prescribes hazards inventory standards for local government plans. Local governments prepared hazard inventories in the late 1970s or early 1980s as part of their comprehensive planning process (see, for example, Lincoln County Hazard Inventory [RNKR Associates 1978]). However, much of the information used for the inventories was general and has proven to be of limited use at the level of detailed site-development.

Planning and Siting of Development

Oregon's statewide land use planning program includes hazard-related planning goals used by local governments to develop local comprehensive plans (LCPs). Three goals apply directly to hazards management. Goal 7, Natural Hazards, mandates that development subject to natural hazards not be located in known areas of natural hazards without appropriate safeguards. Goal 17, the Coastal Shorelands Goal, requires that LCPs consider geologic and hydrologic hazards along the ocean shorelands. When problems of erosion or flooding arise, preference must be given to land use management practices and nonstructural erosion controls. Goal 18, Beaches and Dunes, prohibits development on hazardous dune and interdune lands and prohibits breaching of foredunes except in certain unusual circumstances. Development on more stable dunelands requires findings that such development is adequately protected from erosion and other hazards.

Cities and counties were required to address Statewide Planning Goals in their LCPs, which had to be reviewed and approved by the state. All coastal jurisdictions completed their initial round of planning in the early 1980s and have state-acknowledged LCPs and implementing ordinances. Specific LCP provisions for regulating development in hazardous oceanfront areas vary. All counties have required construction setbacks, either fixed or variable. Some require geologic hazard reports from a registered geologist or engineer, and some use overlay ordinances and other provisions. However, there are few standardized hazard mitigation provisions in the plans and some are more effective than others.

The federal government gets involved in land use management indirectly through provisions of the National Flood Insurance Program (NFIP) (42 USC4001), administered by local governments through the Federal Emergency Management Agency (FEMA). The Upton Jones provision of the law, passed in 1987, authorizes advance payment for relocation or demolition of any structure that is covered by a current NFIP policy and that is subject to imminent collapse because of erosion. However, this provision has not yet been applied in Oregon and it is not likely to be an important management tool. Most of the erosion-related property loss is for bluff-top areas where residents do not have federal flood insurance.

GOVERNMENTAL FUNCTION	FEDERAL GOVERNMENT	STATE GOVERNMENT	LOCAL GOVERNMENT
Research, technical information, and mapping	■ US Geological Survey (USGS)—hazards ■ Federal Emergency Management Agency (FEMA)—flood and erosion hazards ■ Corps of Engineers (COE)—erosion hazards	■ Dept. of Geology and Mineral Industries (DOGAMI)—hazards info and mapping ■ Dept. of Land Conservation and Development (DLCD)—hazards inventory standards ■ Universities/Sea Grant—research	■ Local Comprehensive Plan (LCP)—hazards inventory and maps
Planning and siting of development	■ FEMA—National Flood Insurance Program (NFIP)	■ DLCD statewide planning standards— Goal 7: Natural Hazards Goal 17: Coastal Shorelands Goal 18: Beaches and Dunes	■ State-approved LCP with natural hazards, shorelands, beaches, and dunes elements; local subdivision, zoning, and flood damage prevention ordinances
Design and building criteria	■ FEMA coastal and flood construction standards	■ State Building Code Agency—building standards	■ Local building code administration—city and county
Shore protection	■ COE Nationwide Permit No. 13—bank stabilization	■ State Parks and Recreation Department (SPRD): Beach Law—regulates shore protection structures ■ Division of State Lands (DSL): Removal/Fill Law—regulates revetments and fill	■ LCP and development ordinances (provisions vary)
Emergency planning and response	■ FEMA	■ Emergency Management Division (EMD)—disaster response and planning	■ County emergency services

Table 1. Governmental functions and agencies or authorities for coastal natural hazards management in Oregon.

Shore Protection

The installation of shore protection structures (SPSs) along the oceanfront is regulated by two state laws: the Beach Law (ORS 390.605-390.770) and the Removal/Fill Law (ORS 196.800-196.990). These laws are administered as a joint permit program by the State Parks and Recreation Department (SPRD) and the Division of State Lands (DSL), respectively. The emphasis in both laws is on protecting public beach rights: recreation values and scenic and aesthetic qualities, and safe public access to and along the beach. Both agencies regulate the riprap revetments and seawalls installed along the shore to control erosion and bluff slumping, though their jurisdictions differ somewhat. SPRD regulates all types and sizes of structures, but their geographic jurisdiction is limited to structures that extend west of a beach zone line (BZL) that was surveyed in 1967, just after the Beach Law was passed. DSL, on the other hand, only regulates structures involving 50 cubic yards or more of material, but their geographic jurisdiction is not fixed and extends to the upland vegetation line. Oregon's coastal planning Goal 18 for Beaches and Dunes also plays a role in regulating shore protection. The goal prohibits beachfront protective structures in areas that were not "developed" on January 1, 1977. Development is defined as houses, commercial and industrial buildings, and vacant subdivision lots that are physically improved through construction of streets and provision of utilities to the lot, or areas where special exceptions have been approved. For SPSs, the goal also requires that visual impacts must be minimized, necessary access to the beach be maintained, and negative impacts on adjacent property, and long-term or recurring costs be minimized. SPRD and DSL have incorporated these standards into their own regulations.

The U.S. Army Corps of Engineers (COE) regulates installation of SPSs under section 10 of the Rivers and Harbors Act of 1899 and section 404 of the Clean Water Act (P.L. 95-217). The Portland District COE issued a new nationwide permit for "bank stabilization" (NWP 13), with regional conditions for Oregon, effective February 14, 1992. It replaced a similar 1986 regional permit. NWP 13 effectively removes the Corps from the majority of day-to-day shore-protection decision making.

Policy Implementation Effectiveness

In 1988, with funding from Oregon Sea Grant and assistance from several state agencies and local governments, I initiated an evaluation of the implementation of existing policy for managing development and shore protection along the oceanfront (Good 1992). The objectives of the study were (1) to determine if the goals and objectives of Oregon's shoreline management laws, programs, and regulations are being achieved; (2) to examine the validity of the underlying scientific and management principles on which these laws, programs, and regulations were based; and (3) to provide those who make and carry out ocean shoreline management policy with specific suggestions for improving policy and policy implementation.

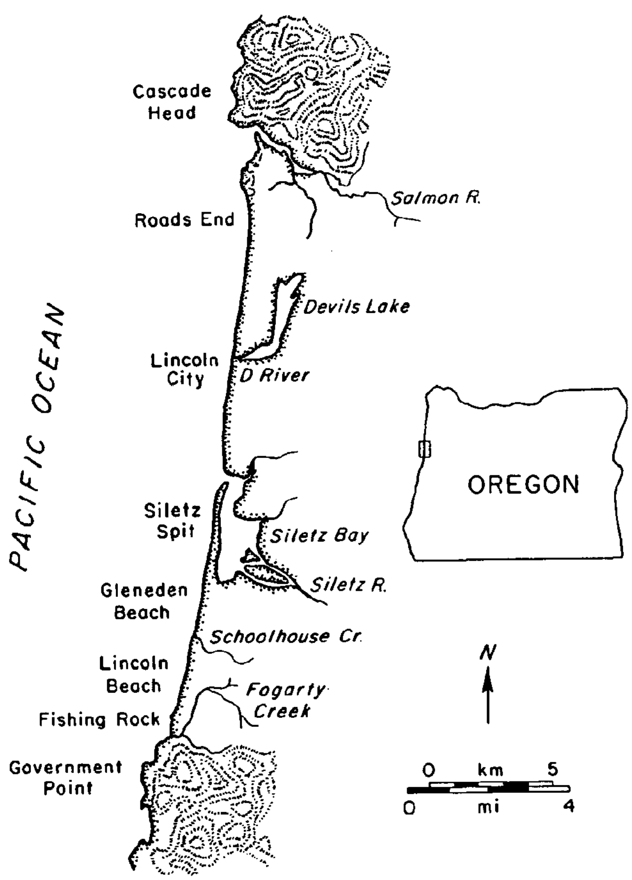


Figure 1. Siletz littoral cell: policy implementation study area.

The principal focus of the study was on the state laws and policies and LCPs that make up Oregon's beachfront "management regime." Policy objectives from each law or policy were identified and synthesized into a single set of shore protection and land use policy objectives. For each objective, possible measures or indicators of policy achievement were identified. Because of the long history of development there, the Siletz littoral cell was selected for the case study (figure 1). Data needs to evaluate achievement of policy objectives were identified, a Siletz cell geographic information system (GIS) was developed that incorporated this data on a tax lot by tax lot basis, and the data were collected and entered into the GIS. A set of queries related to the policy objectives were developed and performed. The results, summarized below, represent the first detailed assessment of how well key policy objectives in Oregon's shore protection and land use laws are being achieved.

Hazard-related Policy Goals and Objectives

Three fundamental goals are central to the suite of laws and rules that constitute Oregon's beachfront "management regime." They are

1) to protect the beach for public recreational use and enjoyment;
2) to conserve, protect, and where appropriate, develop or restore oceanfront lands; and
3) to protect human life and property from natural or human-caused hazards.

The more specific policy objectives in these laws and rules that link decisions with goal achievement are summarized in table 2. These policy objectives are not the exact language of any single statute or rule, but are composite statements from all the statutes and rules examined. Measures or indicators of policy achievement are also listed in table 2. These are the specific qualitative or quantitative data or evidence needed to determine whether or not local and state decisions are actually consistent with policies. The results and conclusions reported here are based largely on data and evidence from queries of the Siletz littoral cell GIS and database.

Are Policy Goals and Objectives Being Achieved?

The policy goals outlined above and the objectives in table 2 are implemented primarily through local land use and related administrative decisions and through shore protection decisions made at the state level. Examination of the outcomes and impacts of decisions made by local governments and state agencies since the inception of the programs, as well as processes used to arrive at decisions, provides useful information for evaluating "implementation success." Some of these findings are outlined below.

Implementation Effectiveness of Oceanfront Development Policies

One of the principal findings of this evaluation study is that in the Siletz littoral cell, there is a strong linkage between local land use decisions and the demand for hard SPSs. These structures, as discussed later, are cause for concern because of adverse short- and long-term impacts on recreational and scenic values, public access, and natural replenishment of beach sand from sea cliff erosion.

There are a number of underlying reasons for this linkage between land use decisions and SPS demand. First, despite the fact that Oregon has one of the most far-sighted set of state land use policies in the United States (DeGrove 1984), including three land use goals that focus on natural hazards, the hazard management strategies actually employed by landowners depend more on structural mitigation than on hazard avoidance. Along the Siletz cell oceanfront, the result has been the proliferation of SPSs.

This connection between land use and SPSs is well understood by planners and others close to the decision-making process and is supported by a variety of evidence. For example, oceanfront construction setbacks for new buildings, whether they follow county or city guidelines or are based on consultant recommendations, are not effective hazard-avoidance mechanisms. In the Siletz cell, where new construction building setbacks met the minimum requirements in the county/city hazard inventory, 40% of the sites later required SPSs to mitigate erosion hazards (table 3). Where county/city setbacks were not followed (usually smaller consultant-recommended setbacks were substituted), 38% later required SPSs. Clearly, neither county/city nor consultant setback procedures work well in limiting the demand for hard SPSs.

The demand for structures is also increased by local policies that sometimes *require* a property owner to install a hard SPS in order to get a building permit. This is because a large number of vacant oceanfront lots are very shallow and virtually unbuildable without an erosion-prevention structure. Because subdivision and lot partition rules do not sufficiently factor in natural hazard concerns along the oceanfront, lots with too little depth continue to be created.

OBJECTIVE[1]	MEASURE OR INDICATOR OF POLICY ACHIEVEMENT
1. Regulate the installation of SPSs	a) process established and used to regulate the installation of SPSs b) numbers, types, and locations of regulated and unregulated SPSs constructed since 1967 (Beach Law) and 1976 (R/F Law)
2. Prohibit hard SPSs for property "developed" after January 1, 1977	a) process established and used to prohibit hard SPSs for property "developed" after January 1, 1977 b) numbers, locations, and situations where SPSs were permitted, but development did not exist on January 1, 1977
3. SPS permits shall not be approved unless compatible with local comprehensive plans (LCPs)	a) process established and used to determine compatibility of SPS proposals with LCP b) numbers, conditions, situations where SPSs permitted, but LCP compatibility not determined
4. Demonstrate the need and justification for shore protection	a) process established and criteria used to determine when a hazard exists and if a shore protection solution is warranted b) the need or justification for approved and denied shore protection permits as reported in findings; or actual physical or other evidence of need c) SPS application approval or denial decisions d) SPS application decisions on vacant parcels
5. Examine and, if reasonable, use alternatives to hard SPSs, including hazard avoidance in land use and administrative decisions	a) processes are established and used to examine and consider land use management and nonstructural alternatives to hard SPSs b) numbers and locations of parcels where new development did or did not comply with required

[1]Objectives were synthesized from policy language in the following statutes and administrative rules:

Beach Law (ORS 390.605-390.770)
Beach Improvement Standards (OAR 736-20-003 to 736-20-035)
Removal/Fill Law (ORS 196.800-196.990)
Removal/Fill Administrative Rules (OAR 141-85-005 to 141-85-090)
Comprehensive Land Use Planning Law (ORS 197)
LCDC Goal 7, Areas Subject to Natural Hazards and Disasters (OAR 660-15-000)
LCDC Goal 17, Coastal Shorelands (OAR 660-15-010)
LCDC Goal 18, Beaches and Dunes (OAR 660-15-010)

Table 2. Oregon's beachfront development and protection policy objectives and measures or indicators of policy achievement.

	hazard avoidance setback, and subsequent SPS needed for both categories c) numbers and locations of parcels that used or did not use relocation as a nonstructural alternative to hard SPS, and the potential for future use of this technique d) numbers, instances where other alternatives to SPSs have been used to mitigate hazards, or, for issued permits, evidence that such alternatives were not feasible
6. Before issuing permits, evaluate, avoid, and minimize the individual impacts of permitted SPSs on public access and recreation use; visual and scenic resources; beach and adjacent land erosion; public safety; other cultural and natural values and resources.	a) process established and used for evaluating, avoiding, and minimizing impacts of each proposed SPS; and for establishing and enforcing permit conditions b) where SPSs interrupt or destroy public access, affected access ways to the beach are retained or replaced; where SPSs encroach on the public beach, lateral access is maintained; instances where SPSs installed at or adjacent to state parks, waysides, or public access points c) qualitative assessment of visual and scenic impacts of individual SPSs d) the design (and construction) of SPSs (size, scale, materials, shape, placement, lateral tie-in) is consistent with hazard and need; encroachment of individual SPSs on public beach; instances, situations where prohibited materials used to build SPSs e) evidence of SPS-induced beach or adjacent property erosion f) siting of SPSs with respect to historical and archaeological sites g) siting of SPSs with respect to threatened or endangered species habitat or other valuable wildlife habitats
7—Before issuing permits, evaluate, avoid, and minimize the long-term, recurring, and cumulative impacts of SPSs on public access and recreation use, visual and scenic resources, beach and adjacent land erosion, public safety, and other cultural and natural values and resources.	a) process established and used for evaluating, avoiding, and minimizing cumulative impacts of SPSs b) cumulative length of SPSs installed along the beachfront by year, type, and landform c) numbers, degree, and area of SPS encroachment on beach (as compared to beach area available) and effects on lateral access and recreational use d) cumulative loss of sand supply to the beach due to hard SPS installation along sea cliffs

Table 2 cont.

Table 3. Construction setbacks and subsequent need for shore protection structures, Siletz littoral cell, 1977-1991.

	LOTS DEVELOPED	SPS NEEDED LATER
County/city setback followed	12	5 (40%)
County/city setback not followed	47	18 (38%)

Structural hazard mitigation is also promoted by interpretations of planning goal language. For example, Goal 7 states that hazardous sites shall not be developed without "appropriate safeguards." Local land use policy, approved by the state planning agency, interprets this language to mean "adequate safeguards." And hard structures are usually deemed "more adequate" than nonstructural mitigation. While this outcome is not inconsistent with the hazard-related land use goal that focuses on the need to protect life and property, it conflicts with the beach protection goal. The net result is more SPSs. Other policy language that implicitly seeks to promote avoidance of hazards and avoidance of hard SPSs ("land use management practices and nonstructural solutions . . . shall be preferred") is relegated to secondary status.

The "hard structure solution" is further institutionalized by the largely uncritical acceptance by local officials of required geotechnical site reports that are based on variable standards and are not subject to quality assurance measures or scrutiny by peers. Revetments and seawalls have simply become the norm. And, as one permit administrator put it, "revetments beget revetments."

Another reason land use practices are driving the demand for SPSs has to do with where the decision-making responsibility lies—almost solely in the hands of local officials. There is a great deal of pressure on these officials to encourage and facilitate growth. Access to the local development decision-making process by state agencies with broader or somewhat different missions is often nonexistent (in the case of local administrative decisions) or limited and costly (through the land use decision appeals process).

Another contributor to problems of oceanfront development siting with respect to hazards is the relatively uncoordinated planning for beachfront areas. Virtually every foot of private beachfront land in the Siletz cell is zoned for residential or commercial development, with little regard for hazards. There are also few effective controls on development practices that threaten the values, resources, and even long-term viability of the adjacent public beach. Little or no regard is given to beach stability factors or wave run-up and erosion potential when development is planned. Finally, plans for adjacent jurisdictions within the same littoral cell are uncoordinated with respect to hazards.

Implementation Effectiveness of Shore Protection Policies

The oceanfront dunes and sea cliffs along the Siletz cell shoreline are the most intensively developed along the Oregon coast—70% of its nearly 900 buildable oceanfront lots are developed. It is also one of the most erosion-prone areas along the coast (Shih 1992). As such, the cell represents a worst-case scenario in terms of development intensity and potential demand for SPSs. Given this situation, how well has the shore protection decision-making process worked in the past? What have been the impacts or outcomes of shore protection decisions? And what might be done to improve the process to better achieve existing and possibly more informed policy goals?

Along the Siletz littoral cell, the shoreline is gradually being hardened with SPSs, mostly large riprap revetments and low concrete seawalls (figure 2). Of the 14 miles of beachfront shoreline, 6.8 miles (49%) have seawalls or revetments installed (figure 3). Figure 3 also illustrates the clear relationship between SPS construction activity and the periodic El Niños that bring short-term elevated sea levels, major storms, and erosion. Because strong or very strong El Niños occur on average every 8.5 years (Quinn et al. 1987), these severe erosion episodes and the gradual armoring of developed and developing coastlines are likely to continue.

The starting point for most discussions about shore protection measures that can be taken to mitigate actual or perceived hazards is the SPRD/DSL joint permit process. With some exceptions, the shore protection process in Oregon is basically a reactive one—property owners, or their consultants or contractors, fill out and submit a joint SPS permit application.

A first observation about the permit process is that it has a number of jurisdictional gaps and overlaps that limit its effectiveness and create needless duplication of effort. Some of these gaps become apparent in a perusal of the governmental functions and responsibilities for shore protection outlined in table 4. Others become evident from queries of the Siletz cell GIS. For example, as a result of jurisdictional gaps in SPS regulation, 3 of 10 oceanfront SPSs built since 1967 in the Siletz cell have not required a state permit (table 5 and figure 4). Almost 50% of these SPSs were built east of SPRD's permit jurisdiction (the beach zone line) prior to 1977, when DSL assumed joint permit authority (table 5). However, because of overlapping jurisdiction since 1977, 63% of the SPS permits have been processed by both SPRD and DSL (table 5). Some of the duplication of effort has been eliminated by a joint application form and a jointly signed permit, but more could be done.

Figure 2. Riprap revetments extend out on the public beach at many points along Gleneden Beach.

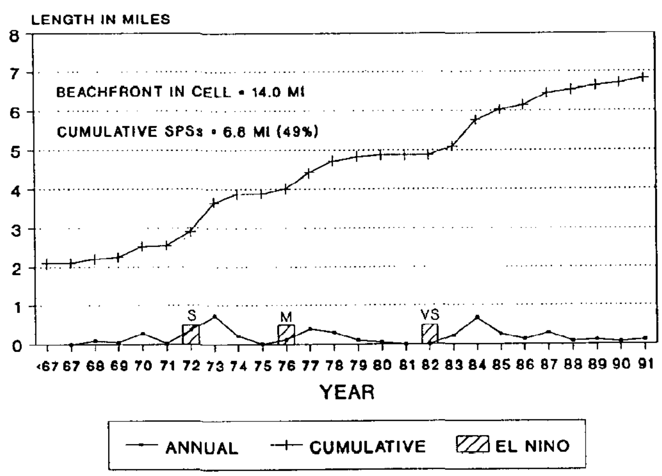


Figure 3. Cumulative and year-to-year length of shore protection structures constructed in the Siletz littoral cell (<1967-1991) and the relationship to the moderate (M), strong (S), and very strong (VS) El Niño events that occurred during the period.

Another finding related to the permit process is that there are no consistent criteria for when "emergency" permits are warranted. The eligibility for emergency riprap of oceanfront lands that were not "developed" as of January 1, 1977 also needs to be determined (see table 2, objective 2).

Jurisdictional gaps and overlaps aside, the permit process for SPSs has serious flaws, beginning with the permit application form itself. The form provides little of the information needed to make a thorough evaluation of the need and justification for the structure, the alternatives to hard shore protection that might be substituted, the proposed design and how it relates to the severity of the hazard or threat, and expected impacts. Although SPRD and DSL do conduct a limited assessment of proposed SPSs, the lack of criteria or structured process for assessing need, alternatives, design, and impacts results in less than satisfactory decisions and outcomes. Some examples illustrate this general point.

With regard to need and justification for a hard SPS, there are no specific criteria to be applied to make this determination (see table 2, objective 4). Absent such criteria, the permit record from the Siletz cell indicates that in 35% of the cases, there was no hazard or actual threat that warranted issuance of an SPS permit. Yet permits were issued. In 28% of the cases examined, the lots for

GOVERNMENTAL LEVEL/AGENCY	TYPE OF PERMIT	TYPES OF SPSs REGULATED	AREA OF REGULATORY JURISDICTION	THRESHOLD OF JURISDICTION
Federal—Corps of Engineers (COE)	NWP 13 w/regional conditions (new/repair)	Riprap revetments; others if notification procedures followed and impact minimal	Below ordinary high water (OHW)—rivers; or high tide line (HTL)—tidal areas	<500 ft in length and <1/2 cu yd of riprap below OHW or HTL
	Regular (new/repair)	Vertical concrete and other retaining walls, all structures not covered by NWP 13	Same as above	>500 ft in length and >1/2 cu yd of riprap below OHW or HTL
State—Parks and Recreation Department (SPRD)	Regular (new only)	All structural types, including sand or other fill	West of the 1967 surveyed beach zone line (BZL)	None—all "improvements" covered, but no permit required for repair to original condition
	Emergency (new only)	All structural types (usually riprap revetments)	Same as above	Same as above
State—Division of State Lands (DSL)	Regular (new/repair)	All structural types, including sand or other fill	Line of established upland vegetation or highest measured tide, whichever is highest	>50 cu yd of riprap or other fill (sand, concrete, etc.)
	Emergency (new/repair)	All structural types (usually riprap revetments)	Same as above	Same as above
Local—city or county	Regular (may defer to SPRD/DSL process)	All types, but varies with city/county	Varies, but may include areas landward of state jurisdiction	Varies

Table 4. Jurisdictional comparison of shore protection regulatory programs in Oregon.

TYPE OF PERMIT

SPSs Built/time period	SPRD regular permit only	DSL regular permit only	Joint SPRD/DSL regular permit	SPRD emerg. permit only	DSL emerg. permit only	Joint SPRD/DSL emerg. permit	No SPRD[1] and/or DSL jurisdiction	Apparent/ possible violation	Total SPSs
1967-76	53	na	na	13	na	na	46	1	113
1977-91	23	20	93	9	3	1	32	16	197
TOTAL 1967-91	76	20	93	22	3	1	78	17	310

[1]SPS project is east of BZL (out of SPRD jurisdiction) or landward of upland vegetation line or highest measured tide (out of DSL jurisdiction)

SPRD—State Parks and Recreation Department
DSL—Division of State Lands
na—not applicable; DSL did not take permit jurisdiction over oceanfront SPSs until 1977.

Table 5. Regulated and unregulated SPSs constructed in the Siletz littoral cell, 1967-1991.

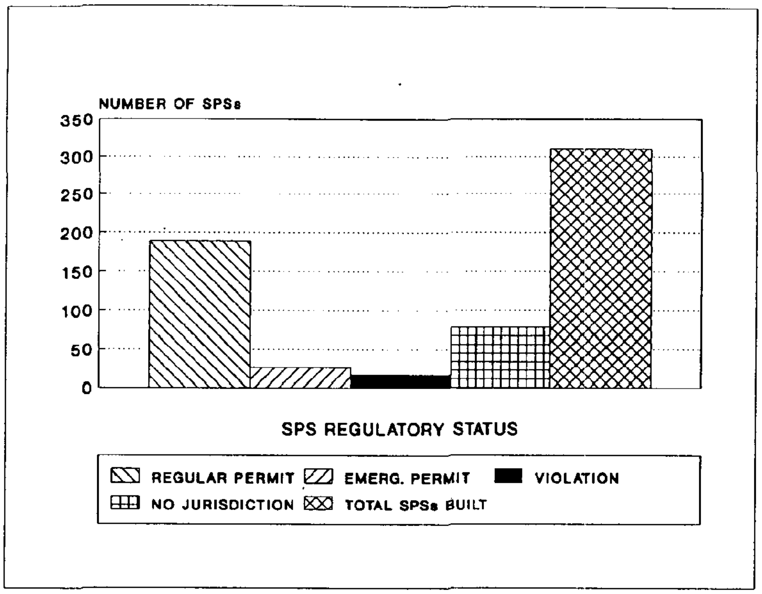


Figure 4. Regulated and unregulated SPSs constructed in the Siletz littoral cell, 1967-1991.

and expertise. Geotechnical reports, sometimes prepared to justify SPSs, generally do not give the rationale for the proposed SPS in comparison with other alternatives considered. Neither do they say why the specified design is needed and rarely do they describe the impacts of the proposed structure. Also, the lack of report standards and provisions for peer review lessens the usefulness of these documents.

which SPS permits were issued were vacant, suggesting that the presence of upland improvements is not an important consideration in the project "need determination." In other cases where there was little hazard or threat, however, the state did take a hard line and denied permits. Yet the erratic record of permit denials over time is further evidence of the lack of consistent decision-making criteria—50% of all denials occurred in a single year and 83% in four years of the 25-year record.

Similarly, there is no process for systematically evaluating alternatives to hard SPSs (see table 2, objective 5), even though Goal 17 (Coastal Shorelands), and SPRD and DSL regulations assert that such alternatives are "preferred." What those alternatives are and situations where they might be applicable have not even been specified.

As with other aspects of the process, the evaluation of potential impacts of SPS proposals is weak (see table 2, objective 6). SPRD does use its beach improvement standards as an evaluation guide; however, while this is helpful, it is relatively superficial and limited by their authority and expertise. SPS designs are not critically reviewed and in most cases are many times larger than needed (figures 5 and 6), resulting in unnecessary public beach encroachment (table 6 and figure 7). The physical impacts of structures are also not evaluated, for lack of both information

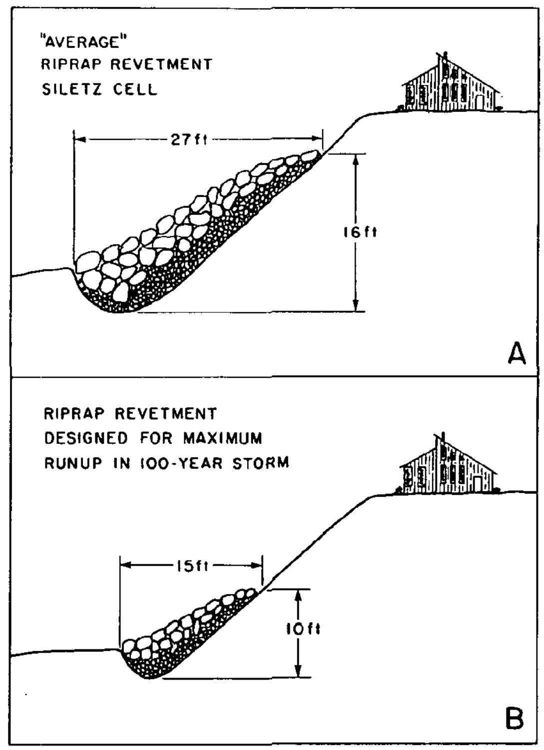


Figure 5. The "average" riprap revetment size for the Siletz cell (A) contrasted with a hypothetical structure sized for maximum wave run-up (see Shih 1992) during a 100-year storm at extreme high tide at Gleneden Beach, Oregon (B).

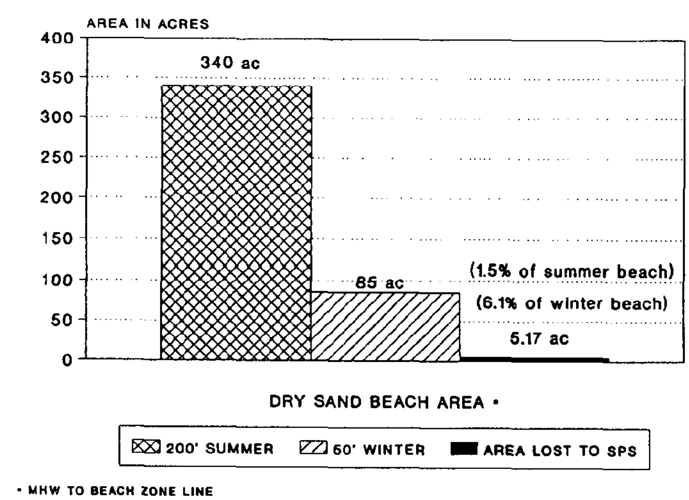
Consideration of the long-term impacts of SPSs, required by state policy, is simply not a high priority for SPRD or DSL given the many more immediate problems with the process and the decisions that must be made (see table 2,

Figure 6. The Furman riprap revetment at S. 44th St. in Lincoln City is an extreme case of an overdesigned structure.

	Distance SPSs Extend West of the BZL (ft)					
	0-10	11-20	21-30	31-40	>40	TOTAL
Numbers of SPSs	61	53	33	9	1	157
SPS-occupied beach west of BZL (acres)	0.76	1.75	1.30	0.90	0.47	5.17

Table 6. Shore protection structures built west of the beach zone line (BZL), Siletz littoral cell, 1967-1991.

Figure 7. Cumulative loss of "dry sand beach" area in the Siletz cell caused by encroachment of shore protection structures west of the beach zone line as compared to the hypothetical summer and winter beach.



objective 7). Nevertheless, study results suggest that long-term, cumulative impacts are potentially among the most serious concerns, especially in a littoral cell like the Siletz where cliff-supplied sand is an important contributor to the sand budget. The gradual loss of cliff-supplied sand to the sand budget due to SPS installation (figures 8 and 9) may eventually lead to beaches that are narrower and less effective as erosion buffers. With the gradual loss of buffering beaches, episodic erosion will likely threaten more and more upland development and result in an increasing rate of

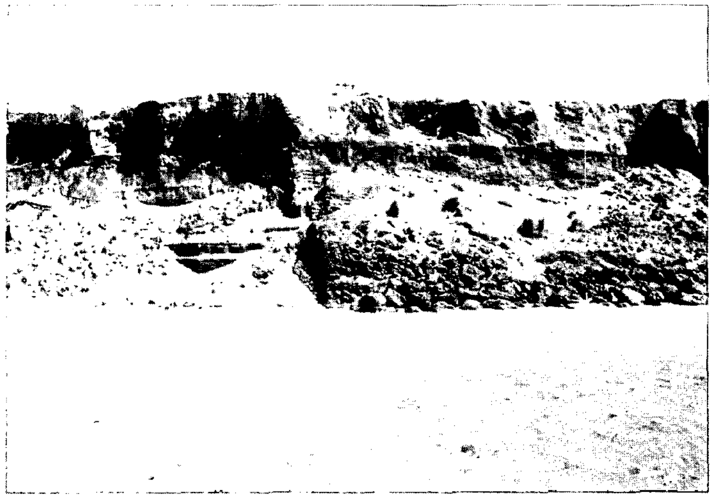


Figure 8. Sand can be supplied to the beach by the eroding cliff on the left; sand supply has been cut off by construction of a riprap revetment at the base of the cliff on the right.

management of coastal natural hazards.

Policy Improvements Suggested by the Siletz Cell Study

A wide array of planning, siting, and design decisions made by individuals, businesses, local governments, and state and federal agencies are—or should be—influenced by coastal natural hazards. Decisions about how coastal lands should be zoned and used over the long term; decisions about the layout of oceanfront subdivisions; decisions on the location, siting, and design of private development; decisions to invest in, finance, and insure development; decisions to protect development, beaches, and recreational resources—all of these are affected by natural processes that present hazards to life and property. Below I suggest policy and policy implementation improvements that respond to the decision-making shortcomings detailed earlier.

SPS installation. The recreational values of the beach will be much diminished.

Improving Coastal Natural Hazards Policy in Oregon

Although there is a substantial base of public policy for addressing many of the natural hazards issues that arise in the siting and protection of oceanfront development, the above critique indicates that improvements are needed in both the substance and implementation of state and local policy. Below I outline some preliminary recommendations, based on my findings in the Siletz cell case study. I also describe a new process Oregon is using to examine and improve its

Establish a simple, clear coastal hazard mitigation policy based first, on hazard avoidance; second, on minimizing the adverse effects of development in hazardous areas; and finally, on compensation for unavoidable adverse effects.

In terms of an overall management strategy, *hazard avoidance should be a fundamental principle* guiding the siting of new oceanfront development along the Oregon coast. This should be the rule for undeveloped raw land, for infill development, or for redevelopment or improvement of existing upland buildings or infrastructure. If, as is often the case, developers cannot completely avoid hazards, then they should—as much as possible—avoid the adverse impacts of hazard mitigation, mainly by the use of

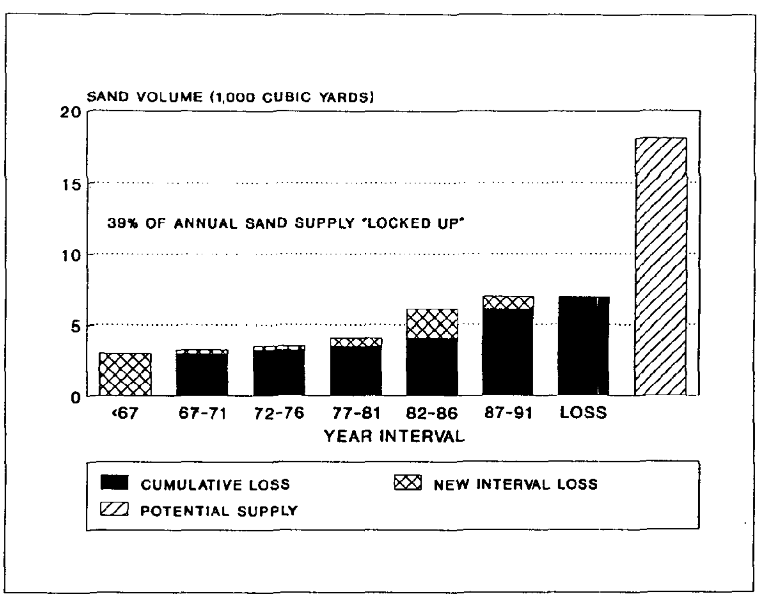


Figure 9. Cumulative loss of sand supply due to construction of shore protection structures in the Siletz littoral cell, <1967-1991.

nonstructural alternatives to hard SPSs. Examples include dune building along the oceanfront to create better buffers against episodic erosional events, bank sloping and revegetation of sea cliffs, relocation of threatened upland structures, and the use of relatively small, dynamic protective structures. If for some reason hard SPSs cannot be avoided, compensation for unavoidable adverse impacts—individual and cumulative—should be required. This hazard mitigation framework is similar to that which has been used for many years to avoid, minimize, and compensate for the adverse impacts on wetland resources. Such a framework could be implemented through the site assessment and setback procedures suggested next, as well as the beachfront planning process outlined later.

Develop a more consistent, structured site assessment procedure and reporting process for development in hazardous areas, incorporating a coastwide construction setback procedure.

Two related tools for implementing the hazard mitigation framework suggested above are (1) an improved site assessment and reporting process for areas subject to hazards and (2) a coastwide building setback procedure. Standards and quality-assurance procedures, including third-party peer review, need to be established for geological and geotechnical site assessment reports. These reports could be used to determine a hazard avoidance construction setback, using a consistent statewide procedure, but applied on a site-by-site basis as a function of applicable ocean, beach, cliff, or other risk factors. Such a setback procedure would recognize the unique situation present at each location but provide overall consistency of siting decisions with respect to erosion, flooding, landslide, and other hazards.

Prepare comprehensive, integrated beachfront management plans for individual littoral cells.

There is a critical need for a more coordinated beachfront development planning process for littoral cells along the coast, especially for shorelines with significant private ownership. These private owners and the local and state officials charged with hazard assessment, beach management, and coastal planning should work together to develop special area management plans for discrete littoral cells. The "special area planning" model is a well-developed and familiar one in Oregon, having been used to develop coordinated plans for each of Oregon's 17 estuaries in the late 1970s and early 1980s (Davis 1980; Gusman and Huser 1984). The model is also the foundation for the wetland conservation planning process the state legislature put in place in 1989 (ORS 196.678-196.681). Beachfront management plans for littoral cells, developed using the hazard mitigation framework suggested above, and based on hazard and sand supply assessments and mapping, scenic resource inventories, public recreation needs, and upland development interests and plans, would resolve many of the shortcomings of present local plans. They would also facilitate more coordinated and conscious decisions with respect to hazards.

Provide for more state oversight of local land use decisions for coastal lands affected by hazards.

While local officials are unlikely to invite greater state oversight and access to land use decisions generally, having such oversight for these few decisions (for example, the siting of oceanfront development) would at least shift the political burden of unpopular decisions to the somewhat more insulated state level. Although this would not remove political and economic influences from the oceanfront siting process, it would provide a buffer for local officials and likely yield more consistent hazard avoidance decisions. Again, analogies can be drawn with the wetland regulatory process, where development conditions are largely determined through the state and federal permit process. Many local governments have been more than willing to leave these decisions with the state because they lack the requisite expertise for assessment and because it distances them from decisions that are often unpopular.

Consolidate SPRD and DSL beachfront shore protection permit programs into a single program at SPRD; eliminate gaps in jurisdiction and enforcement authority.

The regulation of SPSs fits well with the overall beach management responsibilities of SPRD because of their historical emphasis and expertise in evaluating beachfront protection proposals for recreational and access-related impacts and because they have a regular field presence. However, SPRD's jurisdiction over SPSs needs to be extended to all beachfront structures that are likely to affect the resources and values protected by the Beach Law, not just those that extend west of the BZL. Sufficient Beach Law enforcement authority, similar to that in the Removal/Fill Law, also needs to be established. DSL's present role in beach management and regulation, which is comparatively small, could be eliminated if the above gaps were closed. Their program focus and expertise is clearly in the wetlands and waterways arena, not beaches. Wherever the beachfront permit program is housed, responsibility for geologic and engineering review should be assigned to the state agency with the requisite expertise—the Department of Geology and Mineral Industries (DOGAMI).

Clarify policies and improve the evaluation process for SPS permit applications, with emphasis on determination of need and justification, alternatives to hard SPSs, appropriate design of SPSs, and impact assessment.

A policy as to what constitutes "need and justification" for a hard SPS is needed. For example, permit applicants should clearly demonstrate that a hazard exists and that upland improvements are threatened. For officials to implement such policies, standard hazard assessment procedures need to be developed and included in the permit review process.

For situations where a bona fide hazard exists and property is threatened, we need to establish procedures to evaluate nonstructural alternatives to hard SPSs. Alternatives that might be examined include landward relocation, dune building and stabilization, bank sloping and revegetation, selective beach nourishment, and dynamic structures. Where hard SPSs are the only viable shore protection solution, SPS design criteria vis-à-vis the hazard and threat need to be established and used.

The Coastal Natural Hazards Policy Working Group

In response to the problems detailed in this paper—new scientific and technical information on hazards, growing development pressures in hazardous coastal areas, and weaknesses in present hazard mitigation policies and their implementation—Oregon Sea Grant and the state coastal management agency (DLCD) have organized a Coastal Natural Hazards Policy Working Group (PWG). The group is the centerpiece of Oregon's coastal hazards policy improvement strategy, a program that addresses the federal Coastal Zone Management Act amendments of 1990.

The PWG, which includes oceanfront landowners, real estate agents, local officials, a developer, geologists, planners, biologists, and environmentalists, has taken up the task of identifying important coastal natural hazard issues, evaluating existing management strategies and examining alternatives, and then recommending and supporting needed policy improvements to decision makers at all governmental levels. The group will be meeting regularly over an 18-month period.

The PWG is using a highly structured process to develop their policy recommendations. The entryway into the process is an "all-hazards/all-decisions" matrix (figure 10) that is likened to a large window with many panes. To organize the potential chaos associated with all hazards and all types of decisions, the PWG confines itself to a certain section of the matrix for each of its sessions. For example, a PWG discussion session might confine itself to "locating private development in undeveloped areas as it relates to erosion and flooding hazards." Eventually, all of the matrix "windows" get addressed.

The PWG process involves several stages. In stage I of the process (now underway), the PWG generates a list of problems within the selected issue area, groups them by type, and ranks them by relative importance. Using brainstorming, the group comes up with a set of alternatives and, through guided discussion, relates them to the problems. In subsequent sessions, the PWG examines issues and alternatives for each of the remaining portions of the matrix. The product of these sessions is a "working list" of issues and alternatives, organized around natural groupings (education, assessment, planning, protection, and so on).

In stage II (about February 1993), the "working list" will be transformed into discrete sets of

ALL-HAZARDS/ALL-DECISIONS MATRIX FOR CONSIDERATION OF COASTAL NATURAL HAZARDS POLICY ISSUES AND ALTERNATIVES

	CHRONIC HAZARDS					CATASTROPHIC HAZARDS					
PRIVATE/PUBLIC DECISIONS	**Eros**	**Recess**	**Slide**	**Flood**	**SLR**	**Gr-shak**	**Fault**	**Sub/Fl o**	**Liq/set**	**Slide**	**Tsun/Sei**
Locating private development in **undeveloped** areas											
Locating public infrastructure and facilities in **undeveloped** areas											
Designing private development in **undeveloped** areas											
Designing public infrastructure and facilities in **undeveloped** areas											
Protecting private development in **undeveloped** areas											
Protecting public infrastructure and facilities in **undeveloped** areas											
Locating private development in **infill** areas											
Locating public infrastructure and facilities in **infill** areas											
Designing private development in **infill** areas											
Designing public infrastructure and facilities in infill areas											
Protecting private development in **infill** areas											
Protecting public infrastructure and facilities in **infill** areas											
Locating private development in **developed** areas											
Locating public infrastructure and facilities in **developed** areas											
Designing private development in **developed** areas											
Designing public infrastructure and facilities in **developed** areas											
Protecting private development in **developed** areas											
Protecting public infrastructure and facilities in **developed** areas											
EMERGENCY RESPONSE PLANNING											
POSTDISASTER RECONSTRUCTION PLANNING											

Figure 10.

issues, alternative solutions or approaches, and a framework to evaluate their feasibility. At this point public workshops will be held and other opinion-gathering efforts will be made. Then the PWG will decide which alternatives should be advocated for implementation. Finally, in stage III (fall 1993), policies and actions will be packaged and recommended to local and state policymakers.

In summary, the Oregon coast is affected by a variety of natural hazards—chronic erosion, landslides, flooding, and potentially catastrophic earthquakes and tsunamis. Hazard mitigation at the state level is accomplished through state-mandated, locally implemented land use planning and development policy, and state regulatory programs for shore protection. Hazards policy implementation is generally ineffective, particularly with respect to the cumulative effects of hard shore protection structures. Shortsighted land development practices are, in part, driving the demand for hard shore protection. Furthermore, present polices do not address the potential impacts of accelerated sea level rise expected next century or the very real threat of a major subduction zone earthquake and related hazards. To deal with these implementation shortcomings and unaddressed hazards, Oregon Sea Grant and state coastal managers have organized a Coastal Natural Hazards Policy Working Group. The group represents a broad range of interests and is using an all-hazards approach to build consensus and develop recommendations for improved hazards mitigation policy.

This paper is the result of research sponsored in part by Oregon Sea Grant with funds from the National Oceanic and Atmospheric Administration, Office of Sea Grant, Department of Commerce, under grant no. NA89AA-D-SG108 (project no. R/CM-37-PD) and from appropriations made by the Oregon State Legislature. The work was also supported with funds from the Oregon Department of Land Conservation and Development through Section 306 of the Coastal Zone Management Act, administered by NOAA, Office of Ocean and Coastal Resources Management; and in part by funds from the State Parks and Recreation Department, the Division of State Lands, and the Department of Geology and Mineral Industries.

References

Davis, G.E. 1980. Special area management—resolving conflicts in the coastal zone, Environmental Comment No. 10:4-7.

DeGrove, J.M. 1984. Oregon: a blend of state and local initiatives. In Land, Growth and Politics, edited by J.M. DeGrove. Washington: American Planning Association.

Good, J.W. 1992. Ocean shore protection policy and practices in Oregon: an evaluation of implementation success. Ph.D. diss., Department of Geosciences, Oregon State University, Corvallis.

Good, J.W. and S.S. Ridlington, eds. 1992. Coastal Natural Hazards: Science, Engineering, and Public Policy. Oregon Sea Grant, Corvallis, Oregon.

Gusman, S. and V. Huser. 1984. Mediation in the estuary. Coastal Zone Management Journal 11(4):273-295.

Komar, P.D. 1992. Ocean processes and hazards along the Oregon coast. In Good and Ridlington.

Komar, P.D. and S.M. Shih. 1991. Sea cliff erosion along the Oregon coast. In Coastal Sediments '91, 1558-1570. Washington, D.C.: American Society of Civil Engineers.

Kraus, N.C. and W.G. McDougal. 1992. Shore protection and engineering with special reference to the Oregon coast. In Good and Ridlington.

Madin, I. 1992. Seismic hazards on the Oregon coast. In Good and Ridlington.

Quinn, W.H., V.T. Neal, and S.E. Antunez de Mayolo. 1987. El Niño occurrences over the past four and a half centuries. J. Geophys. Rsch. 92(C13):14,449-14,461.

RNKR Associates. 1978. Environmental hazard inventory: coastal Lincoln County, Oregon.

Shih, S.M. 1992. Sea cliff erosion on the Oregon coast: from neotectonics to wave runup. Ph.D. diss., College of Oceanography, Oregon State University, Corvallis.

ISBN 1-881826-00-7